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GGPS: AUTOMATED PLANT IRRIGATION SYSTEM AND BLUETOOTH MONITORING

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***ABSTRACT:** Greenhouse microclimates require precise control, making traditional watering methods highly inefficient. To fix this, we developed GGPS, a smart automated irrigation prototype. Built around an Arduino UNO and an HC-05 Bluetooth module, it enables remote monitoring. Its main innovation is a dual-temperature logic that compares soil and air data to prevent root thermal shock. A built-in sensor also stops the water pump from running dry. Finally, a custom micro-perforated tube ensures even water distribution, while a separated power supply guarantees system stability and optimal water conservation.*

***KEYWORDS:** Greenhouse, Arduino UNO, Bluetooth, Water distribution, Thermal shock.*

1. Introduction

Effectively managing the microclimate inside protected agricultural spaces stands as a critical pillar of precision farming, an urgency heavily amplified by current global climate shifts. Traditional watering strategies, which usually rely on rigid timers or basic manual observation, struggle to allocate resources rationally. In everyday practice, these outdated methods frequently lead to two damaging extremes: wasting massive volumes of water through over-irrigation, or triggering severe crop dehydration. Consequently, optimizing water usage within controlled ecosystems has emerged as a top technological priority. A modern greenhouse demands a strict, dynamic balance between physical soil conditions and internal atmospheric parameters, essentially eliminating the risks tied to human monitoring errors or time constraints.

The primary objective of this research revolves around the design, physical assembly, and experimental validation of an independent electronic water management system, designated as GGPS. Once deployed, the device actively tracks environmental indicators in real time, relying on a custom algorithm to determine the exact optimal moment for pump activation. What truly sets this prototype apart is its core logic: it directly correlates soil moisture levels with ambient air temperature fluctuations. Furthermore, the underlying software architecture features a strict safety routine. Should the system detect any logical errors or dangerous thermal anomalies, it immediately suspends the watering cycle. This vital function protects the electromechanical hardware and completely removes the need for human supervision. To properly demonstrate the technical viability of our solution, the following sections thoroughly detail the mechanical design phases, electrical architecture, climate control algorithms, and wireless communication integration.

2. Current State

Conventional small-scale automated irrigation setups frequently rely on a single drip point placed immediately next to the plant's stem. This specific technical configuration creates a highly localized water saturation zone. Consequently, large volumes of the surrounding substrate remain profoundly dry. Such a physical imbalance severely restricts the absorption capacity of the root system, ultimately depriving the plant of vital nutrients distributed throughout the rest of the soil.

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The GGPS device effectively resolves this design flaw by introducing a hydraulic circuit with an annular geometry. Mechanically, the system employs a flexible polymer tube positioned concentrically on the soil surface. We equipped this conduit with precisely spaced micro-perforations. This spatial calibration guarantees a constant dynamic pressure throughout the entire loop. Once the pump activates, fluid is dispersed isotropically over the entire target zone. Ultimately, this technical approach achieves homogeneous wetting across the cultivation section, significantly boosting root absorption efficiency.



Fig. 1. Assembled physical prototype of the GGPS system

3. Electrical Architecture

The electrical architecture of the GGPS system consists of measurement, control (Arduino UNO), actuation (relay, pump), and power supply blocks. To guarantee sensor accuracy and eliminate electromagnetic interference (EMI) caused by the pump motor, we implemented an independent dual power supply. For absolute stability, a 9V battery powers the

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logic circuit (Arduino and sensors). Meanwhile, the pump's power circuit and the water monitoring system use a separate 6V source.

Bluetooth communication requires signal adaptation. To convert the logic level from 5V (Arduino pins) to 3.3V (HC-05 RX pin), we calculated a voltage divider using 1 k Ω and 2 k Ω resistors, according to equation (1):

$$V_{out} = V \cdot \frac{R_2}{R_1 + R_2} \quad (1)$$

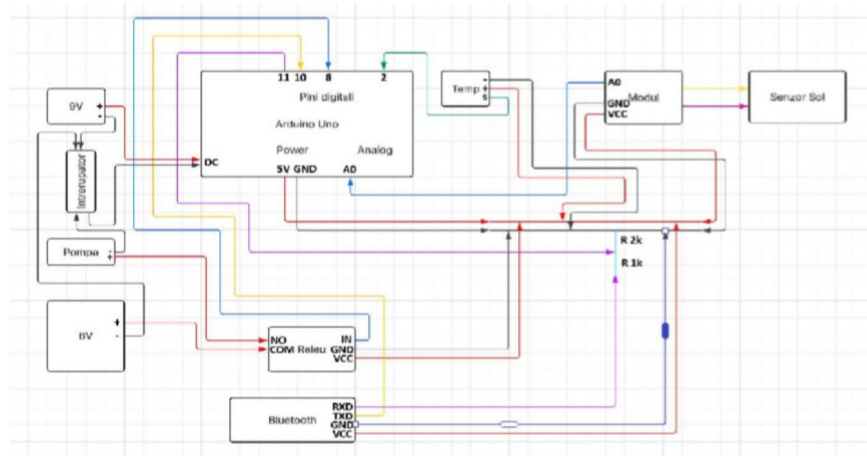


Fig. 2. Electrical scheme of the GGPS project

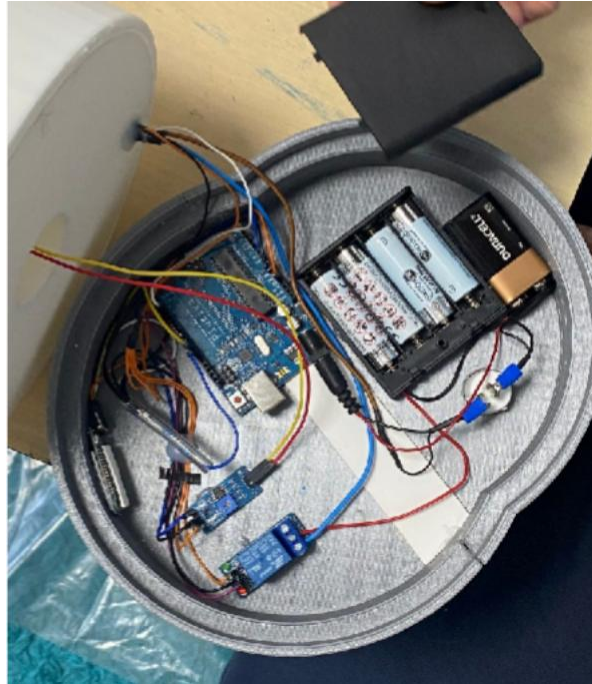


Fig. 3. Physical wiring of the hardware components (microcontroller, sensors, and power supply) integrated into the prototype's base.

4. Operational Logic

Unlike conventional setups that trigger pumping the moment the substrate dries, the GGPS

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device relies on a complex, temperature-conditioned decision algorithm. The microcontroller's software architecture defines a critical soil moisture limit, calibrated exactly at 30%. When the sensor detects a value dropping below this barrier, the program actively prevents the hydraulic circuit from starting immediately. Instead, the central unit prioritizes querying the climate transducers located inside the greenhouse ecosystem. If the ambient thermal regime exceeds the 40 °C threshold—a highly recurrent meteorological phenomenon during the summer season—the irrigation process enters a state of temporary suspension. The scientific reasoning behind this restriction targets the plant's structural integrity directly: infusing standard tap water (typically between 18-22 °C) onto an overheated root mass triggers an acute thermal shock. This sudden physiological stress destroys the delicate absorbing capillaries. Consequently, it severely blocks nutrient assimilation and forces a rapid vegetative collapse of the entire crop. Driven by clear protective considerations, the safety algorithm delays the wetting cycle until the atmosphere cools down below the optimal 35 °C barrier, at which point the watering intervention proceeds safely.

5. Bluetooth Monitoring

The GGPS hardware continuously acquires meteorological and pedological data, processing them internally before instantly dispatching the payload to a mobile platform via Bluetooth. We implemented this information exchange using text-based serial packets, rigorously structured according to the CSV standard. Within this specific format, thermal and hygrometric parameters are concatenated sequentially, utilizing the comma as the primary delimiter. Such an approach significantly minimizes radio transfer complexity, while simultaneously guaranteeing an extremely stable communication speed at the classic 9600 baud rate.

On the receiving end, the graphical user interface (designed entirely within the MIT App Inventor environment) integrates a custom timer module. Calibrated to a 1000-millisecond sampling frequency, it cyclically queries the Bluetooth connection. Upon detecting a valid data packet, the algorithm partitions the incoming character string based on the delimiter. It then precisely routes these values toward predefined graphical fields (Labels): Ambient Temperature, Air Humidity, and Soil Moisture. This dynamic refresh procedure strictly alters the numerical variables alone, leaving the explanatory text blocks completely intact. As a result, the algorithm completely neutralizes the visual flickering effect, a technical flaw commonly encountered with conventional serial displays.

5. Mechanical Design and CAD Modeling of the Assembly

The mechanical design phase deliberately optimized part geometry to withstand high greenhouse humidity. Specific dimensions and assembly tolerances are meticulously detailed across Fig. 4, Fig. 5, Fig. 6, and Fig. 7. All subassemblies were 3D-printed using PLA polymer, a material selected specifically for its excellent structural and ecological stability. These custom enclosures guarantee a rigid fixation of the electronic hardware directly onto the planter. Consequently, they effectively prevent any accidental short circuits during the active irrigation cycles.

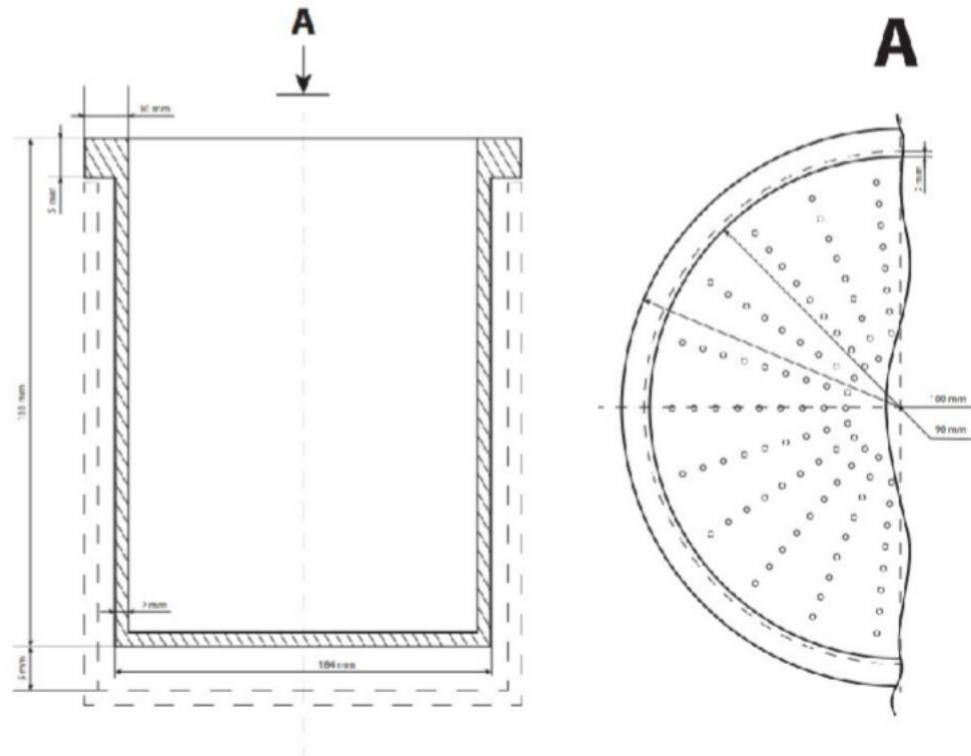


Fig. 4. Execution drawing and dimensions for the inner body of the assembly

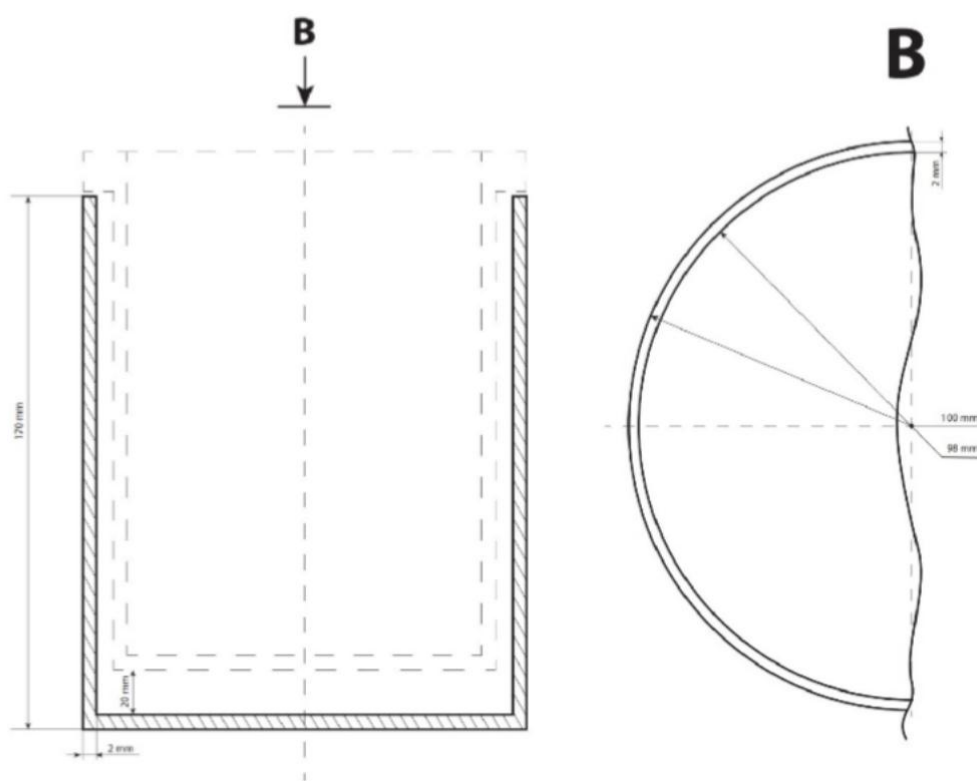


Fig. 5. Execution drawing and dimensions for the outer body of the assembly

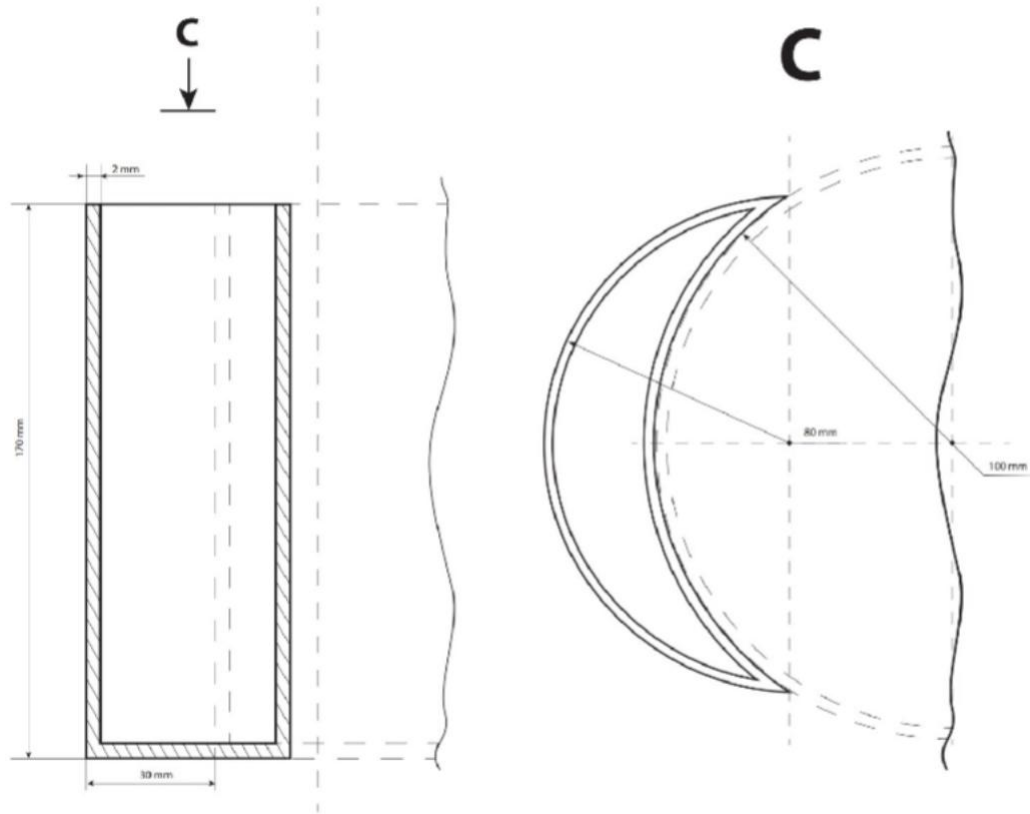


Fig. 6. Execution drawing and dimensions for the power supply body of the assembly

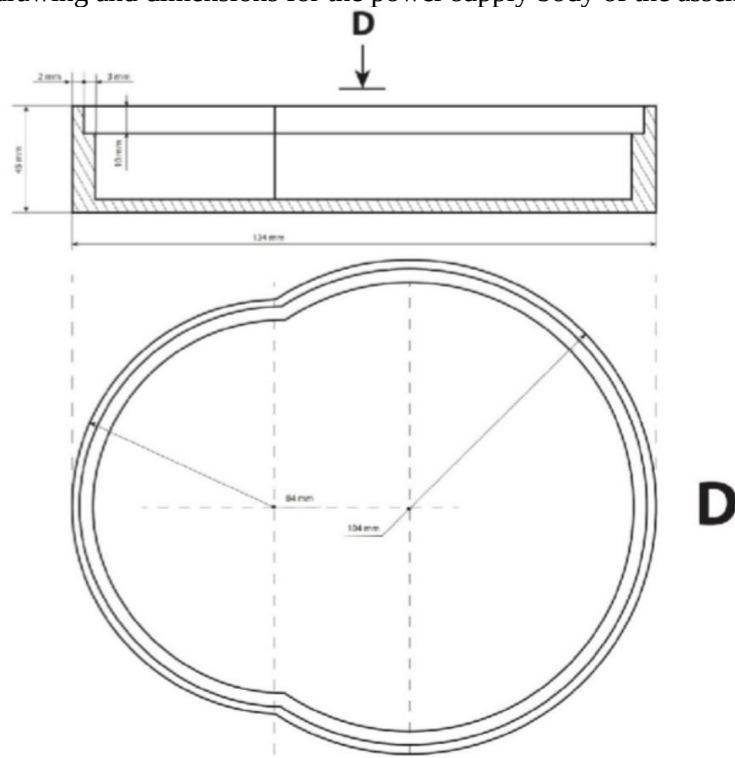


Fig. 7. Execution drawing and dimensions for the base of the assembly

6. Production Cost Analysis

From an economic standpoint, the GGPS prototype was strictly optimized for maximum affordability. This makes it an ideal solution for small-scale farmers, while simultaneously allowing for future large-scale deployment. By managing all monitoring functions entirely through software (the mobile application and the microcontroller), we completely eliminated the need for expensive physical displays—like LCD screens or HMI panels—and complex industrial controllers.

The final cost of the prototype encompasses only the fundamental electronic components (the Arduino development board, the HC-05 Bluetooth module, and the humidity/temperature sensors), alongside the control relay, the submersible pump, and the raw PLA polymer used for 3D printing. Ultimately, this low-cost approach, combined with the sheer energy efficiency of the dual power supply, ensures a rapid return on investment through substantial long-term water savings.

7. Conclusions

This research successfully demonstrates the viability of implementing a smart, automated water management system specifically tailored for protected greenhouse environments. By developing a dual-microclimate analysis algorithm, the GGPS device effectively overcomes the operational limitations of classic models. Above all, it provides genuine biological protection for crops against acute thermal shock.

Separating the main electronic board's power source from the pump's supply entirely eradicated electromagnetic interference. Thanks to this engineering solution, the hardware performed flawlessly throughout all testing phases, without the software generating a single error. Furthermore, integrating Bluetooth technology enables a highly accessible, modern monitoring experience directly via a smartphone. Looking ahead, we aim to integrate an SD card module to actively log historical sensor data. Additionally, we plan to expand the current project scope so that a single central unit can simultaneously control multiple independent watering zones across a larger greenhouse facility.

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9. Notations

The following symbols are used throughout this paper:

V_{in} = input electrical voltage (signal from the Arduino pin) [V];

V_{out} = output electrical voltage (stepped-down signal routed to the Bluetooth module's RX pin)

[V];

R_1 = value of the first resistor in the voltage divider circuit [$k\Omega$]; R_2 = value of the second resistor in the voltage divider circuit [$k\Omega$];

AUTOMATIC TRASH CAN

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Abstract: Our project is a trash can that opens automatically when a hand approaches the motion sensor. This performs the lifting and lowering maneuver, during which time the user of the bin can throw away toxic waste without having to put his hand on the bin and transmitting or taking bacteria from the bin. This trash can is most often used for children, because they are the most inattentive when it comes to hygiene Thank you for your attention!

Key words: automatic, trash can, Arduino

1. Introduction:

In this project we have made an automatic trash can that opens without touching, using a motion sensor like this (fig. 1).

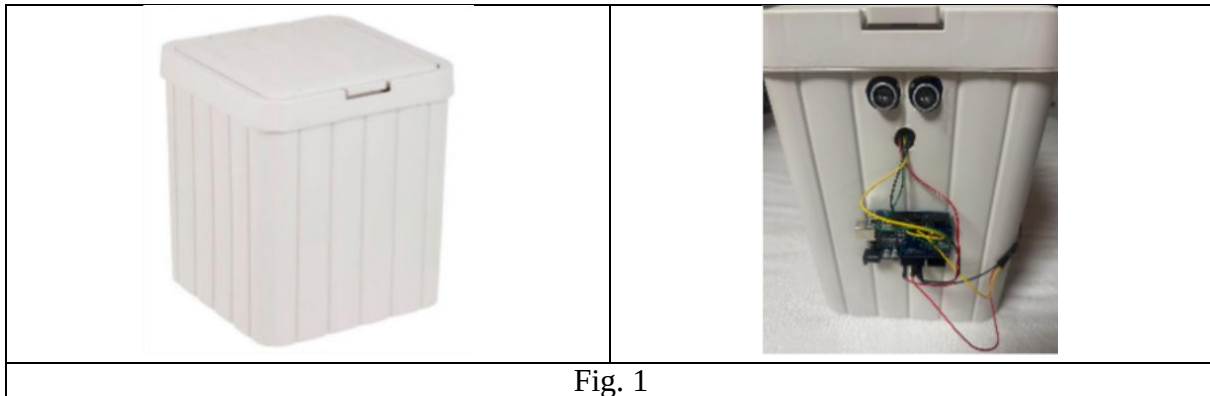
The purpose of this project is to improve people's hygiene and comfort, eliminating the need to touch the lid of the bin and the risk of as many bacteria on the lid of the bin.

This device is very useful in the following places: kitchen, hospitals, schools, kindergartens.

2. Operating principle

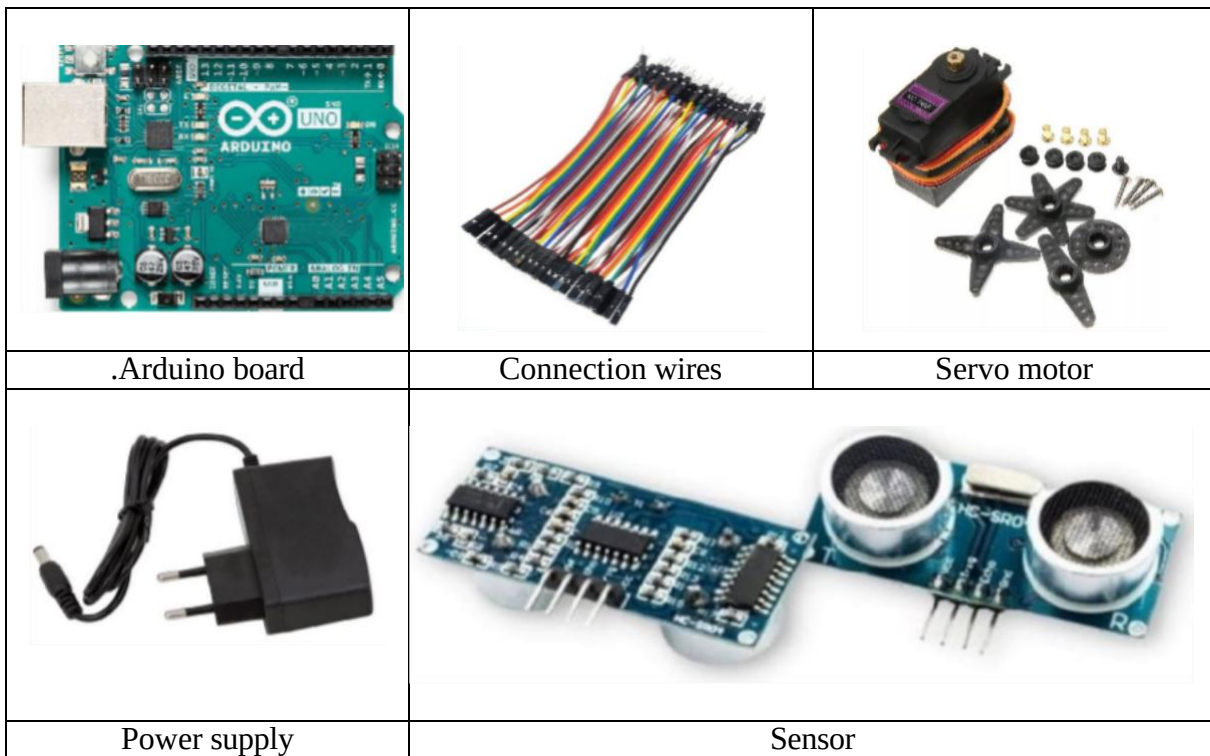
1. The sensor detects the user's hand
2. Sends a signal to the Arduino
3. Arduino processes the information
4. The servo motor opens the lid
5. After a few seconds, the lid closes automatically
6. The process is repeated as many times as needed.

AUTOMATIC TRASH CAN



3. Required components:

1. Arduino board
2. Sensor
3. Servo motor
4. Connection wires
5. Power supply



4. Electrical diagram

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Ultrasonic sensor:

1. VCC $\rightarrow$ 5V
2. GND $\rightarrow$ GND
3. TRIG $\rightarrow$ Digital pin 11

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4. ECHO → Digital pin 10

Servo motor:

1. Red wire → 5V

2. Brown wire → GND

3. Orange wire → Digital pin 9

5. Physical implementation

For the practical part:

1. The servo motor is fixed on the lid

2. A connection is made between the servo motor and the lid

3. The arduino and the wires are mounted inside the basket

4. The sensor is placed in front

6. Advantages

-High hygiene

-Easy to use

-Low costs

-Easy to make

-Does not take up much space

7. Disadvantages

-Requires power

-The sensor can give errors

-Repeated verification of the assembly

-Consumes constant energy

-Damage to the wires over time

Concluzie:

We can say that it can be made in even larger sizes.

It has an important role in the health and education of the child to throw away the leftovers in the trash to emphasize

To encourage children to throw away the trash and become more responsible we can put both lights and music on the trash can.

It can also be made in larger sizes.

In the first semester of the first year, we participated in technical drawing and infographics courses, materials science, as well as industrial engineering basics, and in the second semester of the first year, we participated in materials strength and materials technology courses.

8. Notations:

- Height: 28 cm
- Width: 20 cm
- Length: 20 cm
- Volume: 10 L
- Side area: 22400 mm
- Total area: 22800 mm
- Base area: 400 mm

Bibliography:

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- [7]. *** Note de curs disciplina „Tehnologia materialelor”

GRAIN DISPENSER

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SUMMARY: *This paper addresses the importance of optimizing the feeding process in rural poultry microfarms, where the feed is varied and requires a complex mixture of 4-5 ingredients (grains and vitamins). The main objective of this project is to design and build an automated installation capable of accurately dosing the quantities of cereals according to a predefined recipe, to make the mixture and send it to a hopper, from where it enters directly into a pellet machine for animal feed. To achieve this goal, we experimentally developed the single-section feeder, a device that is presented in detail in this paper.*

KEYWORDS: *automation, optimization, bird feeding, agricultural tools, rural development.*

1. Introduction

Agricultural technology has evolved a lot in recent years, but rural households still stick to old, manual methods. The daily feeding of birds is very varied and requires the correct combination of 4-5 ingredients (cereals, vitamins and other resources usually found in the household).

As an alternative to complex industrial systems, the project proposes an accessible installation, which also offers protection against humidity or pests (such as rats). The equipment measures the components according to the indications of a nutritionist, homogenizes them, and the resulting mix is discharged into a secondary hopper from which a pellet machine is directly fed. The following pages present in detail the prototype made for a single section of this feeder.

A. The main objectives of the project are:

- To release exact portions of grain, according to the recipe;
- To relieve people from heavy physical labor every day;
- To keep animal food in a clean and closed environment;
- To have a low manufacturing cost.

B. To create this device, the following steps were taken:

- 1) Documentation of the quantities of food offered to the animals;

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- 2) Conceptual design on paper, dimensioning of parts, calculation of dimensions and areas;
- 3) Geometric modeling of the dispenser in the "Autodesk Fusion" program;
- 4) Printing of parts using a 3D printer and assembly of the first physical prototype;
- 5) Reconfiguration of the dosing system and modeling of an improved version (based on initial tests);
- 6) Optimization and integration of hardware for device automation.

2. Past and current stages

Prototype 1: Concept Test. This is the first prototype, a miniature version of the project. At this stage we did not use electronic parts, and the drive mechanism had not yet been designed. The main purpose of this model was strictly visual and practical: we wanted to observe how the parts fit together.



Fig. 1. Prototype 1

Prototype 2: First movement tests. Later we moved to a larger scale version, in order to add the electronics for the drive mechanism. It was an important step because motors were added to this prototype. They were temporarily glued with adhesive and we were able to demonstrate how it works. One problem encountered was: the overall dimensions were too large. Because of this, the pinion and rack did not align correctly, and the movement was not transmitted properly. The design had to be changed later on.

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Fig. 2. Prototype 2, without electronics

Prototype 3: Stable and improved version. The dimensions were redesigned and adjusted, leaving more space so that all the components could be mounted much easier and correctly. The main improvements were:

- **More secure fixation:** We gave up on glue and attached the motors with screws;
- **Increased stability:** We built a solid support, in the form of a 4-legged frame, that supports the assembly;
- **Better organization:** We added special cases to protect and keep all the parts fixed.

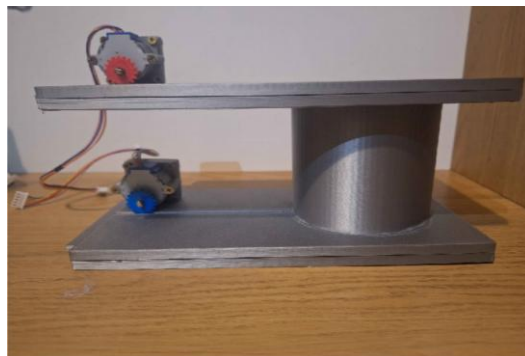


Fig.3. Prototipul 3

3. Mode of operation

A. Main components and their role :

- **Main Tank (Hopper):** Located in the upper part, it stores the entire quantity of grain to be dosed;
- **Dosing Cylinder (Volume Chamber):** Located between the 2 closing gates, the segment is mounted vertically. Its internal volume determines the exact quantity of a portion of grain.
- **Closing Gates (Upper and Lower):** Two identical mechanisms mounted at the ends of

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the cylinder;

- **Actuating Mechanism:** Each gate is controlled by a motor through a system coupled to a wheel (pinion and rack). The rotation of the motor moves the wheel, transforming its circular movement into linear movement, thus the opening gate plate comes out.

B. Operating Steps:

1. *Initial State (Standby): Both gates are closed, the dosing cylinder is empty;*
2. *Opening the first gate: The upper motor is activated, the first gate is opened. The grains fall from the tank (under the action of gravity) from the tank into the cylinder. The cylinder is filled to its maximum capacity.*
3. *Volume Isolation: After the cylinder is filled, the upper motor reverses its rotation and closes the first gate.*
4. *Opening the second gate (Discharging the portion): The lower motor is activated, the second gate is opened. All the grains accumulated in the cylinder fall into the final container placed below.*
5. *System reset: The lower motor reverses its rotation and closes the second gate. The system returns to its initial state and is ready for a new dosing.*

4. Dimensioning and Tables

A. Classification of parts:

- **Closing Gates(ET-01 si ET-03);**
- **Dosing Cylinder(ET-02);**
- **Main Tank(ET-04 si ET-05).**



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Fig. 4. Supply Cylinder Sketch

Fig. 5. Dosing Cylinder Sketch

B. Parts Sizing (Tabele):

Parts	Diameter		Height	Volume	Weight
ET-01	Inner hole: 220 mm		30 mm	$4799,6 \times 10^3 \text{ mm}^3$	38,06 kg
ET-02	220 mm		400 mm	$15205,3 \times 10 \text{ mm}^3$	120,58 kg
ET-03	Inner hole: 220 mm		30 mm	$4799,6 \times 10^3 \text{ mm}^3$	38,06 kg
ET-04	Small: 220 mm	Big: 250 mm	250 mm	$45317,4 \times 10^3 \text{ mm}^3$	359,37 kg
ET-05	500 mm		700 mm	$137.444,68 \times 10^3 \text{ mm}^3$	2.136,28 kg

Lenght ET-01/ET-03:

660mm Width ET-01/ET-03:

30mm

C. Ecuations:

$$V_c = \frac{\pi \cdot D^2 \cdot h}{4} \quad (1)$$

$$V_{tc} = \frac{\pi \cdot h_2}{12} \cdot (D_1^2 + D_1 D_2 + D_2^2) \quad (2)$$

$$G = \rho \cdot V \quad (3)$$

$$\rho = 7,85 \times 10^{-6} \text{ kg/mm}^3 \quad (4)$$

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D. Bill of Materials Table ET-01 (Table):

ET-05. Material Price=38,06 kg * 8 €/kg = 304,48€ = 1586,34 lei

1. Material	1586,34 lei		
2.TSQ	31,72 lei	2% [1]	
3.Labour	301.,4 lei	19% [1]	
4.Tax	210,98 lei	70% [3]	Sum 1-5 = 2914,08 lei
5.Administation	a)180,84 / b) 602,8	60 % / 200 % [3]	
6.Profit	1457,04 lei lei	50 % [2914,08]	
7.Total	4371.12 lei		

7. The complete system

Below the storage hopper is the dosing system. The main role of this block is to precisely measure the exact amount needed for the food recipe. The system is set to release only the desired weight of the basic ingredients needed by the birds:

- Corn
- Wheat
- Barley
- Oat
- Nutritional supplements (vitamins and minerals)

Although such an industrial plant can be enlarged and have multiple work lines, the current project focuses on a clear section. The technical drawing shows the front view of the system, with exactly 4 dosing sections being framed. This layout shows how the modules are aligned in parallel to work simultaneously, each section being responsible for a specific ingredient in the recipe.

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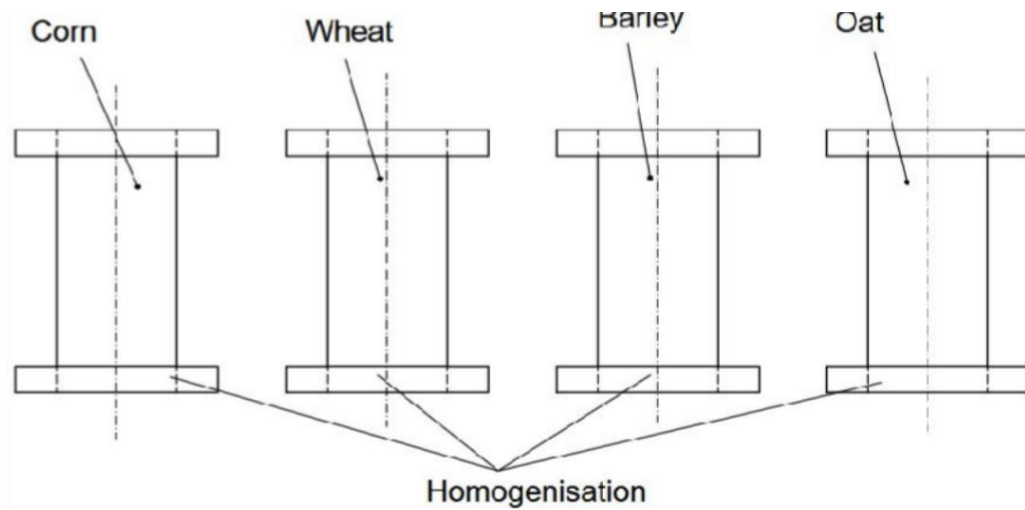


Fig. 6. Dosing sections

After the ingredients have been measured and released from the 4 sections, they fall together into a hopper located below. In this hopper, the homogenization (mixing) process takes place. The grains and supplements are spun until the composition becomes completely uniform, thus ensuring that each serving of food will contain an equal amount of nutrients.

The last stage of the integrated system is represented by the pelletizing machine, where the mixture arrives directly from the hopper. This machine strongly presses the composition and transforms it into compact pellets.

This final format is ideal for birds because:

- It prevents birds from choosing only certain grains.
- Reduces waste and dust in shelters.
- Makes food easier to transport and store long-term.

8. Conclusions and Difficulties Encountered

The creation of the physical prototype of the "Grain Dispenser" demonstrated that the idea is a good one and that such an automated system can greatly facilitate the work of microfarms.

However, the transition from computer drawing (in the Autodesk Fusion program) to the actual creation of the model brought a series of problems:

- **Joining the parts:** When 3D printing the first components, we noticed that some were either too small or fit together. This happened because, during the design phase, we forgot to leave tolerances between the parts. We had to redo the drawings and adjust the dimensions so that the parts could join together correctly.
- **3D printer limitations:** The 3D printer we had was too small to print our bulky parts (like the main tank or cylinder) in one piece. For this reason, we had to cut the large models into smaller pieces, print them separately, and glue them together. It was tedious work, took a lot of time, and in terms of appearance, it didn't look good.

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- Assembly errors: When gluing the parts, the adhesive accidentally flowed onto the other components, which led to the involuntary bonding of two parts that should have moved freely. The closing gate could not be detached from the dosing cylinder, and the model was subsequently rebuilt.



Fig. 8. The glued parts

- Difficulties with the electronics: When we got to the automation of the closing/opening system, it didn't work right away. We discovered that current was being lost along the wire path, which meant that the motors weren't receiving enough energy to move the mechanism. We had to carefully check the circuits and redo the electrical connections.

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10. Notes

The following symbols are used in this work: V_c

- volume of the cylinder [mm^3];
- D – the diameter of the cylinder [mm];
- h_1 – cylinder height [mm].

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V_{tc} – volume of the truncated cone [mm^3]; D_1 – small diameter [mm];

D_2 – large diameter [mm];

h_2 – height of the cone truncated [mm].

G – the weight of the assembly [kg]; ρ – density of the material [kg/mm^3];

V – the volume of the assembly [mm^3].

SMART DEVICE THAT MONITORS THE POSITION ON A MOBILE PLATFORM IN A FACTORY

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REZUMAT: Our project focuses on monitoring every movement of an extendable mobile ladder with the help of an accelerometer and gyroscope module that extracts the data with the help of XYZ coordinates. The system will send alerts to its designated app when the module is getting an input that reaches values over a set limit. These values were manually configured with the help of a set of trial and error, where we were able to figure out what kind of movement was damaging to the ladder. This way our monitoring system can prevent further damage and any possible accidents related to said ladder.

KEY WORDS: monitoring, sensors, testing optimal parameters, wear prevention

1. Introduction

Our project is focused on the configuration of a 6-axis inertial sensor type MPU6050. The code was made in Arduino IDE, a modified version of C++. We are using the Serial Monitor to see the logs and for a quick read on the position of our object where the device is placed. The MPU6050 incorporates a triaxial accelerometer (on the XYZ axes) and a gyroscope. The device is powered by the ESP32 microcontroller and the communication is carried out via the I2C protocol. The purpose of the work is to monitor the position of the object on which the device is placed and test the optimal parameters, in order to prevent sudden or premature wear of the machine. The entire assembly is powered by an external battery (Power Bank) connected to the ESP32, which provides a voltage of 5V through the USB port.

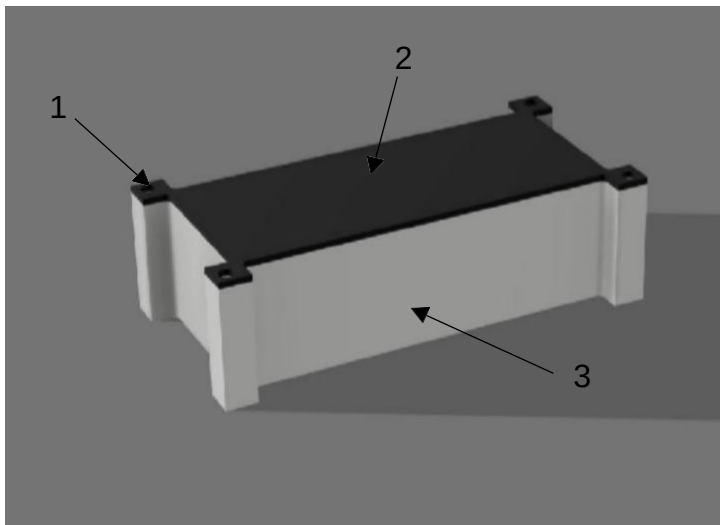
Wiring:

- 3.3V $\rightarrow$ 3.3V
- GND $\rightarrow$ GND
- SDA $\rightarrow$ PIN 4 (SDA)
- SCL $\rightarrow$ PIN 3 (SCL)

SMART DEVICE THAT MONITORS THE POSITION ON A MOBILE PLATFORM IN A FACTORY

2. CAD/ DESIGN

In order to create the box for our monitoring device, we used a 3D printer. The box was printed via PLA filament, modeled in Autodesk Fusion. Moving on, the 3D model was exported in a .stl file and transferred in the CreaLity Print slicer where we prepared it for printing. In order to print the box, we used 10% infill with a gyroid pattern (this pattern is especially good for what we are looking for since it provides the much needed strength at a minimal material used).



Box components:

- 1- Hole for screw and nut
- 2- Lid
- 3- Box

The 3D model was designed with 2 vital conditions in mind: the battery should be easily accessible and easy to attach to the platform. The box should be easy to open in order to charge the battery, but it shouldn't open by itself, so we added holes for screws and nuts, this way we fixed both problems.

3. Programing:

The Arduino code configures and reads data from the MPU6050 inertial sensor using the ESP32 microcontroller, converting the raw values into standard units of measurement (m/s^2):

3.1. Libraries and Initial Configurations

- `#include <Wire.h>`: Includes the standard library for communication via the I2C protocol.
- `const int MPU_ADDR = 0x68;`: Defines the default I2C hardware address of the MPU6050 sensor.
- `int16_t raw_ax, raw_ay...`: Declare 16-bit signed variables to store the raw acceleration and gyro axes (since the sensor sends 16-bit data).
- `LSB_G = 16384.0`: This is the default sensor scale factor for sensitivity of $\pm 2g$. At this setting, the raw value (16384) is equal to $(1g)$.

SMART DEVICE THAT MONITORS THE POSITION ON A MOBILE PLATFORM IN A FACTORY

3.2. The setup() function (Initialization)

- `Serial.begin(115200);`: Starts serial communication at 115200 baud to display logs in Serial Monitor.
- `Wire.begin();`: Initializes the I2C bus on the ESP32 pins (pins 3 and 4 mentioned in your wiring diagram).
- Wake up the sensor: The MPU6050 starts in "Sleep" mode by default. The code writes the value 0 to the power management register (0x6B) to fully enable the sensor.

3.3. The loop() function (Periodic data reading)

- Request data: Sends a request to the sensor starting at register 0x3B (where the acceleration data starts) and requests 14 bytes in total. These 14 bytes contain: acceleration (6 bytes), temperature (2 bytes), and gyro (6 bytes).
- Bit recomposition: Since each axis is sent as two separate bytes (8 HIGH bits and 8 LOW bits), the code uses the left shift operator `<< 8` and the bitwise OR operator `|` to combine the two bytes into a single, full 16-bit value.
- Temperature Ignore: The two consecutive `Wire.read();` lines skip the temperature data because your project is only concerned with position and motion.

3.4. Math Conversion and Display

- Acceleration calculation ($\sqrt{m/s^2}$): Divides the raw value by 16384.0 to get the acceleration in units of $\sqrt{g}$, then multiplies it by 9.81 to convert the result to meters per second squared ($\sqrt{m/s^2}$).
- Display: Sends the calculated values for the X, Y, and Z axes directly to the Serial Monitor with two decimal places.
- `delay(200);`: Pauses execution for 200 milliseconds between readings to avoid cluttering the screen and monitor the data at an easy-to-read rate (5 readings per second).

4. Current status

For now our project can only send alerts to users within the coverage area of the local wifi router. A priority direction of development could be changing the method of sending data, such as storing it on a server, so the data can be fully verified remotely, and adding a notification function when the ladder is taken into a restricted area.

The main objective of the project is to prevent work accidents, as incorrect use of the ladder can lead to wheel wear or other common damage.

SMART DEVICE THAT MONITORS THE POSITION ON A MOBILE PLATFORM IN A FACTORY

The system also contributes to optimizing the workflow by detecting movements generated by inappropriate use of the ladder and automatically sending alerts to the designated application, so that timely action can be taken.

5. Conclusion

The system made simplifies the monitoring and prevention of wear of an extendable mobile ladder. By using the MPU6500 sensor and the ESP32 microcontroller, the project provides a practical solution for detecting misuse and transmitting alerts in real time. The total cost of the system is approximately 220 lei, which makes it affordable and easy to implement. The project can be developed by extending the data transmission distance and adding a notification function when the ladder is taken into a restricted area. The aspect I encountered difficulties with was the programming part.

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- Materials Technology Course
- Strength of Materials Course

LEVEL OF AWARENESS IN EMERGENCY SITUATIONS

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Emergencies are spontaneous events, with an instant effect that can occur at any time in any situation, so it is important to know the basic concepts and information that could save our lives, but also the lives of others. Unfortunately, this knowledge is weak, erroneous or even outdated. This paper identifies the level of awareness of such situations by age group, presents the errors and mistakes found in the way of thinking formed based on outdated knowledge and proposes solutions for improvement and change. In conclusion, the level of this knowledge must be monitored and renewed according to the deficiencies discovered, but this must be done by adapting the proposed solutions.

KEYWORDS: knowledge, awareness, situation, emergency.

1. Introduction

In the current context, characterized by an increasing diversification and modification of natural, social, and especially technological risks, the population's capacity to respond as efficiently as possible in a crisis situation becomes a total priority.

Among the factors that distinguish a controlled event from an unprecedented catastrophe is, primarily, the level of awareness in such situations.

Also called „Situational Awareness”, it does not represent just a simple state of alert, but a complex cognitive process[1].

The issue of situational awareness involves passing the event to which a person is exposed through the filter of perception, followed by the understanding and assimilation of the situation they are in, then anticipating the possible risks that will befall them, and finally, reacting.

The efficiency of the response manifested once reaching the reaction state is often sabotaged by psychological barriers such as „decision paralysis” or „normacy bias” [2], [3], reactions which demonstrate that the simple existence of information is not enough and does not guarantee an appropriate reaction.

This paper aims to identify the level of awareness, or more simply put, of knowledge, of individuals by age groups in emergency situations, to expose the problems and errors in the information underlying the mentality in such situations, and finally to find and propose solutions to change this mentality and rectify the incorrectness of the information already acquired by those involved.

In order to fulfill the proposed objectives, we designed and distributed a questionnaire to a total of 80 people of different ages, with questions addressing knowledge of different emergency situations, opting for variation and extension in coverage instead of fixating on a specific event.

Thus, following the centralization of the data, the answers were graded with one point per correct answer, the possible total being 10 points.

After centralization and grading, statistics could be created based on which we drew pertinent conclusions related to the identified problems, and finally, we were able to reach the proposal of some solutions for the identified problems.

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2. Current status

The current status of the problem is marked by a transition from providing information (warning) to the management of attention and behaviour, with the human factor remaining the biggest problem.

Although warning systems have become increasingly accurate, the phenomenon of desensitization of the population appears due to the high frequency of RO-ALERT messages, which had led to ignoring them, a phenomenon known as „alert fatigue”[4].

Thus, the focus has begun to be placed on personalized alerts, in order to reduce information noise.

3. Presentation of results of interest

Next, we will present the statistical results obtained from the centralization of the received answers.

The presented results are those of increased interest and which touch upon the theme of this paper.

In the age category section, the majority of 68% answered 18-30 years old, with 21% failling into the 50+ years old group, 10% in the 31-50 years old group and only 1% belonging to the 10-17 years old group.

From these responses, we can observe that the survey reached a very large percentage of the young population segment, which is susceptible to media and internet influences.

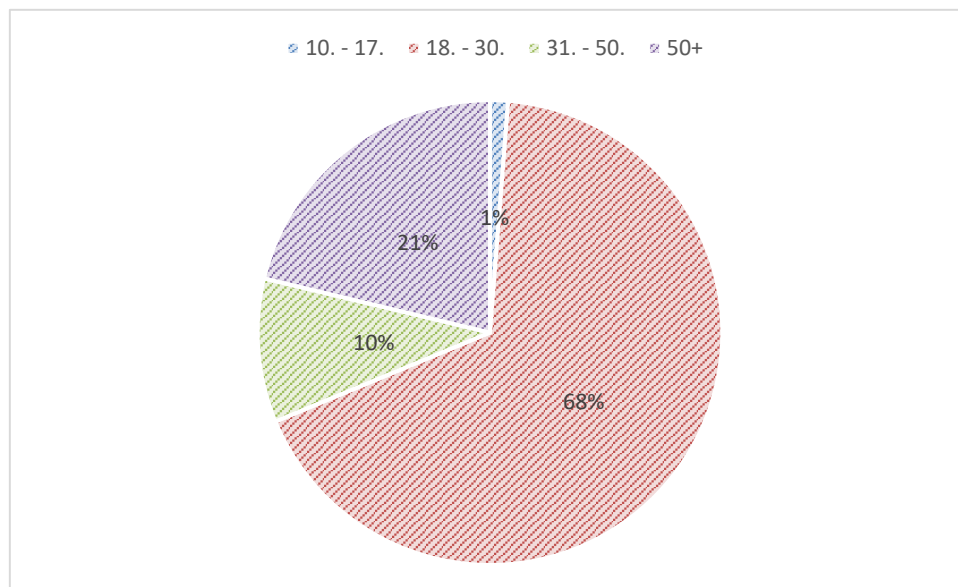


Fig. 1. Age groups chart

QUESTION 2 – How should you move to exit a smoke-filled room?

The majority (81%) answered correctly, with only 19% answering incorrectly, because the option to walk out standing up while holding your breath may sound faster and easier, but in fact it is very dangerous, because it brings to light a new number of risks, such as loss of consciousness due to lack of oxygen, collision with objects, walls or other people, tripping and others [6].

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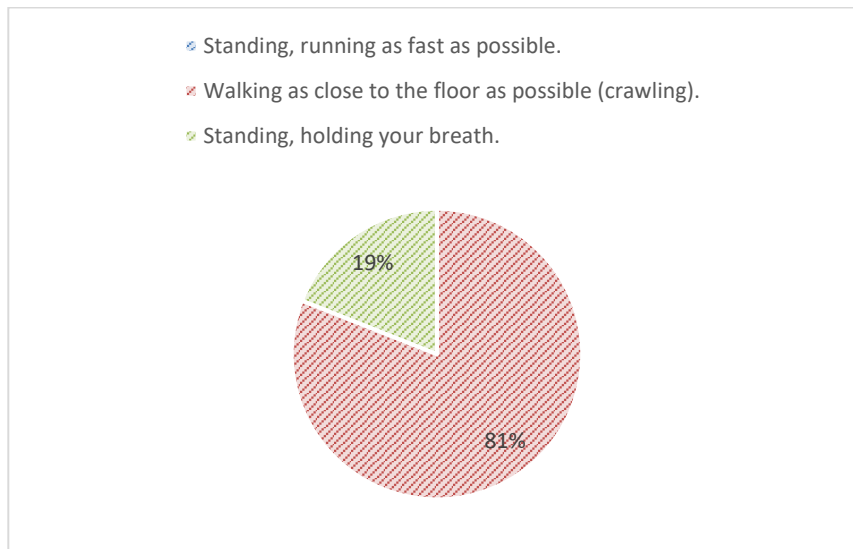


Fig. 2. Chart of answers for question 2

QUESTION 3 – What do you do if your clothes catch fire?

The answers are divided, with 77% answering correctly regarding the course of action in such situations, but it is good to point out that the 23% did not answer completely wrong either, because in the situation where the clothing that caught fire is a glove, a hoodie, an item of clothing that is very easy to take off, the option chosen by the 23% becomes viable, but only then [6].

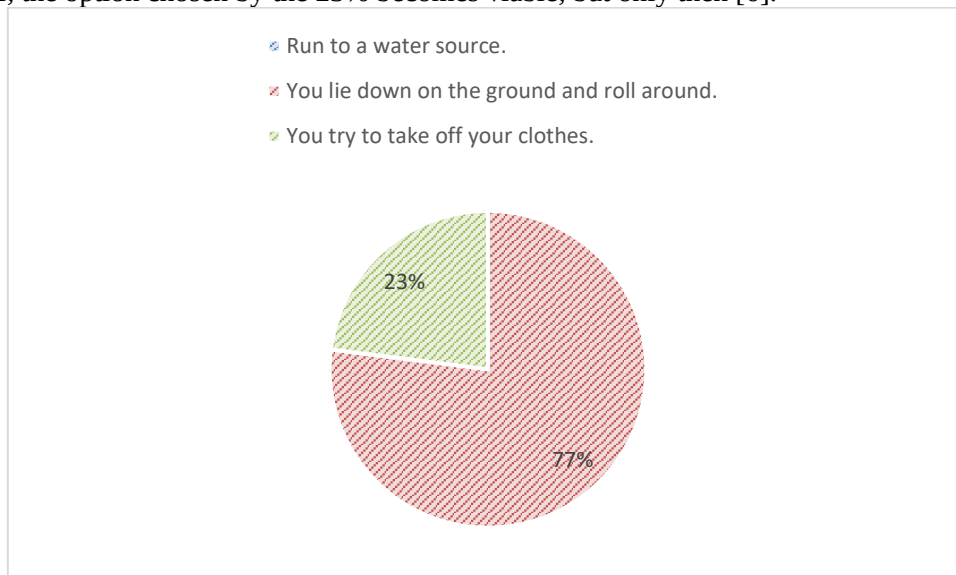


Fig. 3. Chart of answers for question 3

QUESTION 4 – Where is the safest place to take shelter in a room during an earthquake?

At this question, the presence of outdated information based on which people were prepared can be seen very clearly.

In an earthquake situation, the option to take shelter under a desk, table or door frame becomes a challenge depending on the circumstances in which the exposed person finds themselves and, most importantly, it becomes a danger, because the weight that can fall on the table, desk or door frame, can be great enough to crush the person and the environment used for shelter.

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Therefore, the best option is to lean against the walls in the corner of the room, away from windows, furniture or any other element, because even if a heavy weight, a part of the ceiling, or a wardrobe falls, it will lean on the edges of the walls that make up the corner, creating the so-called triangle of life [7].

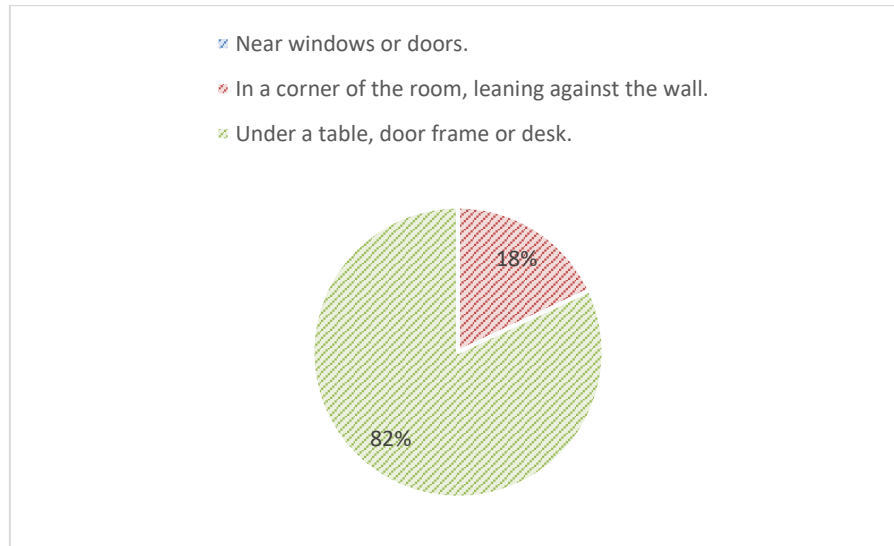


Fig. 4. Chart of answers for question 4

QUESTION 6 – What must I check first when finding an unconscious person?

Everyone's natural instinct would dictate that in such a situation they should go and check if the person in question is still breathing, if they are conscious, if they have a pulse, all of these, without asking themselves if they themselves are putting themselves in danger, exposing themselves to the same event that put the person in question on the ground.

Another problem is that an ordinary person, a normal human being, does not have the knowledge and experience necessary to be able to check a pulse [5].

This skill is acquired through constant experience, which not everyone can do unless they work in a field where they meet this challenge daily.

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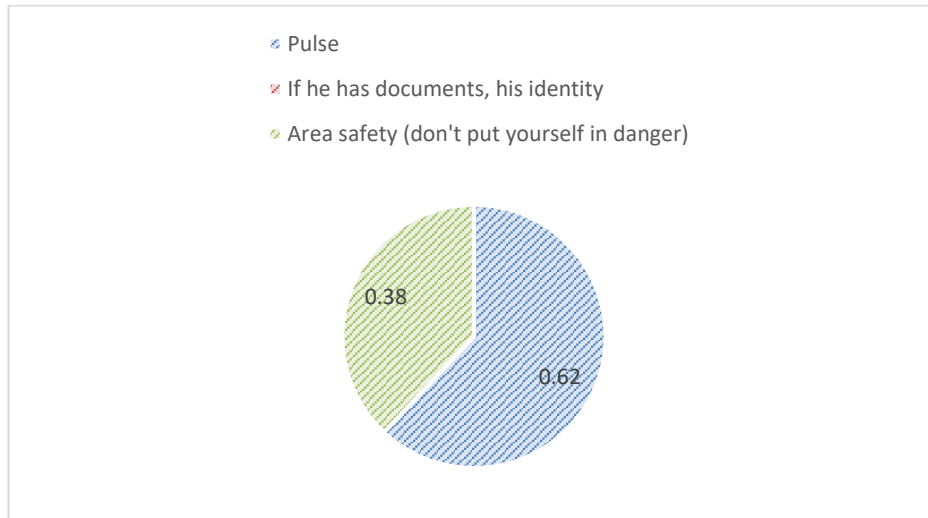


Fig. 5. Chart of answers for question 6

The remaining questions do not require an increased approach because the answers received were in correspondence with our expectations, so only possible discrepancies in the statistics need to be addressed, but these are small and easy to manage.

Finally, we want to present the score groups into which the participants fell, the groups are as following:

- Group A: 0 – 4 points, very weak level of awareness;
- Group B: 5 – 6 points, weak level of awareness;
- Group C: 7 – 8 points, good level of awareness;
- Group D: 9 – 10 points, very good level of awareness.

As can be seen in Fig. 6., out of the participants, a very limited number fell into Group A, the majority found themselves in Group C, a minority entered Group D and the rest are found in Group B.

From these, we can say that over 70% of the participants have a good level of awareness, with a part of them having a very good one, but needing information and re-verification of knowledge, focusing on the subjects where they had gaps, with the 30% needing careful training and monitoring of the evolution of progress.

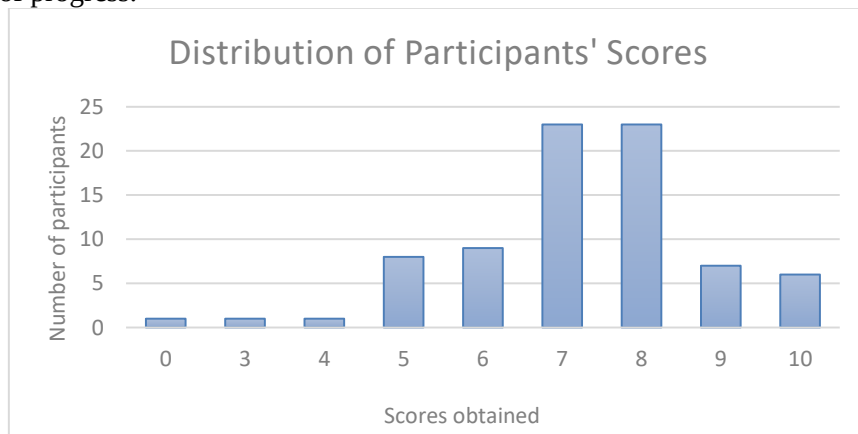


Fig. 6. Scores chart

4. Conclusions

LEVEL OF AWARENESS IN EMERGENCY SITUATIONS

In conclusion, although the number of participants was quite limited, we were able to obtain a useful number of answers based on which to identify problems that we can later address with measures adapted to the current social and technological climate.

Thus, as mentioned in the introduction, we want to propose the creation of brochures with information related to emergency situations, adapted according to age groups and, most importantly, containing practical examples, not just empty theory.

These will be distributed to the participants, especially to those classified in score Groups A and B. But, as is very well known, merely informing them is not enough; a new, more complex and longer form will be created, which will be distributed to the participants of this paper to be filled out, thus ensuring the verification of progress.

The results will be presented in another research paper, being a continuation of this one, but an attempt will also be made to carry out a paper on the same theme, but which will reach a much larger number of participants, preferably 200 participants.

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FROM PERCEPTION TO RISK : ANALYZING THE CORRELATION BETWEEN SAFETY CLIMATE AND THE INCIDENCE OF OCCUPATIONAL ACCIDENTS

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ABSTRACT: This study analyzes the impact of organizational safety climate on the incidence of accidents within the construction industry, combining national statistical analysis with an in-depth study of a real workplace accident. The objective is to demonstrate how employees' perceptions of management priorities directly influence preventive behavior. The results indicate that a positive safety climate serves as a more reliable predictor of occupational health and safety than mere legislative compliance. The conclusions advocate for a transition from a sanction-based system toward an organizational culture focused on conscious risk management, providing practical solutions for reducing critical events.

KEYWORDS: safety climate, construction, work accidents, organizational culture.

1. Introduction

The construction sector has recently been experiencing several problems related to work accidents, although one of the main pillars of the economy, it remains the most vulnerable area. Despite technological advances and increasingly strict legislative measures, high accident rates indicate a problem that goes beyond the technical sphere, the human factor and organizational culture.

Most of the time, the pressure of completion deadlines, prioritizing productivity instead of security creates an environment in which employees perceive safety as a formality, not as a basic value, This difference between written rules and the reality that we find on construction sites is directly influenced by the perception of workers on risks, but also on the decisions that must be made in critical moments.

By analyzing a case study, based on a real event, we will observe how climate deficiencies can transform a predictable risk into an undesirable event, with serious consequences.

2. Case study analysis – The accident at the National Library of Romania

On August 13, 2021, at the National Library of Romania in Bucharest, a work accident occurred in which several workers, employed by a subcontractor company, suffered a fall from a height of approximately 8-10 meters, the unsecured embankment collapsed on top of the workers who were carrying out maintenance work on the building's facade.

Analyzing the correlation with the Safety Climate, but also of the data published later, it can be seen that the work was carried out without a construction permit, which indicated a managerial attitude ignorant of the legislative norms, in favor of the rapid completion of the project.

The intervention of the rescue crews was significantly hampered due to the lack of protective measures at the workplace. The embankments had not been secured with adequate support elements, although this is an elementary and mandatory protection measure. In the absence of these reinforcement structures, the earth walls became extremely unstable, transforming the entire area into an extremely dangerous perimeter not only for the workers, but also for the search and rescue teams that arrived later. Ignoring this technical detail blocked the immediate access of the firefighters, who were forced to prioritize their own safety before being able to intervene to extract the victims.

The workers' decision to descend into the trench to weld a pipe reflects a serious problem when it

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comes to risk perception. They consciously accepted the possibility of a behavioral collapse that leads to the discovery of a harmful work and organizational climate, in which the completion deadline takes precedence over security, in this context, life becomes a secondary variable, in front of the objectives to be achieved at the workplace.

3. Statistical data and correlation analysis

According to reports to the Territorial Labor Inspectorate (ITM) and the Ministry of Labor, the construction sector recorded 20% more accidents in 2024, compared to accidents recorded during 2023, thus recording an alarming increase in fatal accidents.

Table 1. Situation of accidents in construction

Period	Number of injured people	Deaths
2023 (the first 9 months)	4019 (total labor market)	-
2024 (the first 9 months)	191 (construction)	7

This difference between norm and reality confirms the theory that a harmful safety climate, which is measured by time pressure and lack of weekly inspections, becomes a concise indicator of work accidents. Climate that is characterized by:

- Time pressure, where pressing deadlines and the focus on profitability lead to a forced pace of work, exerting rapid work pressure on teams of workers, most often to the detriment of safety measures.
- The lack of regular and effective inspections, which attest to the fact that if they are not carried out weekly, or if they are not strict enough to identify and correct hazards that may arise in time, they lose their preventive role, so that workers may come to believe that some irregularities are accepted or, most often, encouraged.

4. Personal note and critical evaluation

Following the analysis of the event that occurred on the construction site at the National Library, with the help of the theory regarding the safety climate, I believe that the main pillar was not the omission made by the worker, but the omission of management. When a work starts and carries out its objectives without a maintenance authorization, but also without measures to fix the banks, a clear message is highlighted to the workforce: "production is more important than your life". In my view, the solution does not lie in more legislative violations, although ITM applied sanctions of over 6 million lei during 2024, but in changing the way the worker perceives authority. Safety at the workplace regardless of the workplace must become an assumed value, not a rule to be imposed. In the case of the National Library, a healthy safety climate would have allowed each worker participating in the work to refuse to enter the unsecured trench, without fear of the administrative repercussions that may result from the refusal.

5. Images from the accident scene

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Image 1. The construction site where the accident occurred

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Image 2. Search-save operation

6. Conclusion

After analyzing, I noticed a clear connection, when time pressure is the main thing on the construction site and inspections are only a facade, employees can no longer or perhaps do not want to comply with technical regulations. These working conditions make the rules ineffective, transforming them from safety tools into simple ignored formalities.

Although the risk was obvious, leading to the idea that the accident could have been avoided, the management's omission turned this possibility into a real accident. It is like hanging a heavy object on a spider's web, although you know that it is fragile and ready to give way, without trying to add repairs to stabilize it. Instead of preventing the collapse, you actively contribute to it. In the case I studied, this "spider web" was not given the necessary attention, leading to an accident with serious consequences, the injury of 4 of the employees and the death of 2 of the 6 workers involved.

To prevent accidents of this kind, through future research I propose to carry out anonymous perception questionnaires, which can provide valuable information to management, about how employees perceive safety, what their fears are when they show up at work, but also what suggestions they want to offer for good functioning and for easier communication.

To ensure accuracy of the information, the future study is also based on the collection of primary data. The data will be collected directly from the source, namely from workers and supervisors on construction sites using questionnaires applied in the field.

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Risk of Accidents Caused by Overpressure in Pharmaceutical Manufacturing Lines

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***ABSTRACT:** This paper presents the occupational safety risks associated with the manufacturing of sterile parenteral pharmaceutical products, with emphasis on pressure-related incidents occurring during the aseptic filling process. The study describes the technological flow used in the production of prefilled syringes containing ibandronic acid solution and analyzes a real case involving overpressure generated during solution transfer between storage and filling vessels. The causes of the incident, including human error and improper pressure release, are discussed together with the corrective and preventive measures implemented afterward. In addition, the paper highlights the importance of GMP regulations, personal protective equipment, personnel training, ergonomics, and process safety management in pharmaceutical manufacturing facilities. The study underlines the necessity of continuous risk assessment and strict compliance with safety procedures in order to protect both operators and product quality.*

Key words: risk, accidents, drug, production, occupational, health, safety

1. Introduction

Rompharm Company SRL was founded in 2004, in Ilfov County, Otopeni. It is a company that deals with the production of medicines, currently managing seven departments, each of which is intended for the manufacture of various pharmaceutical forms, such as ophthalmic preparations, parenteral preparations, solid preparations or oncological drugs, as well as the packaging department.

The pharmaceutical industry is an essential field for the health of the population, and the manufacture of medicines, especially sterile parenteral preparations, requires compliance with strict standards of quality, safety and microbiological control. Since these products are administered directly into the body, without natural protective barriers, technological processes must comply with GMP, European Pharmacopoeia and occupational health and safety rules.

In medicine factories, equipment that operates under pressure, such as preparation vessels, autoclaves and transfer systems, is used, and the associated risks include overpressure, contamination or failure of the facilities. These situations can affect both the safety of personnel and the quality of the products.

The paper analyzes the risk of overpressure in the manufacturing line of sterile preparations, with a focus on the aseptic filling process of pre-filled syringes with ibandronic acid. The technological process, the equipment used, a case study of an overpressure incident, as well as the causes and corrective measures applied are presented. The aim is to highlight the importance of compliance with GMP and HSS, personnel training and process monitoring to prevent accidents and ensure safety in the pharmaceutical industry.

2. About Rompharm Company

Although there are many companies in Romania that manufacture products with the same active substance, Rompharm is positioned on the Romanian market as an important distributor of generic drugs, representing strong competition for other manufacturers of analogue substances, in terms of quality and price. With over 160 drugs in its portfolio, the factory has a sales market that extends both in Europe, namely in the European Union, and on the Asian continent, in countries such as Russia, Georgia, Uzbekistan, Kazakhstan and others. Although it does not actually deal with the development of new pharmaceutically active

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molecules that it then subjects to preclinical and clinical tests in order to be approved and then distributed to the population, the Rompharm company continuously invests in equipment, so that the quality of the formulations and generic products manufactured by them is at the highest standard and meets the needs of patients in terms of drug supply.

3. Description of parenteral drugs

Parenteral preparations are sterile pharmaceutical products with critical quality requirements regarding sterility, endotoxins, particles and integrity of the container-closure system, intended for administration by routes that bypass the gastrointestinal tract. The most common parenteral routes of administration are: intravenous, intramuscular, subcutaneous, and less common - intracardiac, epidural, etc., and the preparations can be in the form of a solution, oil-in-water emulsion, very fine suspensions, powders, etc. The production of parenteral drugs is the most demanding, because there are many precautions and rules that must be followed, to ensure the strict conditions of sterility and pyrogenity imposed by the European Pharmacopoeia - 12th edition and the Romanian Pharmacopoeia - 10th edition, without visible particles, with a controlled number of subvisible particles, formulated so as to be isotonic or close to physiological tolerance (when necessary), with compatible pH, chemically, physically and microbiologically stable. A preparation is considered sterile when the sterility test value is 0 colony forming units (CFU) (bacterial or fungal). It is important to remember in GMP / QC that the sterility test does not "prove" the absolute sterility of the batch but is a sample compliance test, but the factory, through additional precautions, tests the solution with which the pumps and filling needles are primed. Real sterility is mainly based on: validated aseptic process, process simulation (media fill), sterilizing filtration / terminal sterilization, environmental monitoring and container integrity. Endotoxins are those microbial fragments, from Gram negative or even positive bacteria, fungi and certain biological impurities, that the body's immune system detects as foreign and dangerous to the body and thus triggers a febrile response, which for a critically ill patient can be fatal. For endotoxins there is a limit that differs depending on the route of administration (the intrathecal route has a limit of 0.2 EU/kg/hour, while most parenteral products have a limit of 5 EU/kg/hour). The manufacture of these types of products requires knowledge in the pharmaceutical, industrial engineering, chemical engineering, and more, which are intertwined in this process, starting from the actual preparation, to aseptic filling, in the case of products intended for direct administration into the blood, to the control and labeling phase. Although the production parameters, such as temperature and pressure, are very clearly defined and the processes are largely automated, there are also risks associated with human error, which fortunately, in this case are not serious. Next, it is described the manufacturing process of pre-filled syringes with 1% ibandronic acid. This is a drug from the bisphosphonate class, useful in osteoporosis, prevention of bone events in patients with metastases and sometimes for the treatment of tumor-induced hypercalcemia. Ibandronic acid can be administered both orally and by injection, the mechanism of action being the same: it inhibits osteoclasts, reduces bone resorption and decreases bone mass loss. Each route has its advantages and disadvantages, which are presented in the table below. Preparatele parenterale sunt produse farmaceutice sterile cu cerințe critice de calitate privind sterilitatea, endotoxinele, particulele și integritatea sistemului container-închidere, destinate administrării pe căi care ocolesc tractul gastrointestinal. Căile parenterale de administrare cele mai comune sunt: intravenos, intramuscular, subcutanat, și mai puțin comune - intracardiac, epidural etc, iar preparatele pot fi sub formă de soluție, emulsie de tip ulei în apă, suspensii foarte fine, pulberi, etc. Producția de medicamente parenterale este cea mai pretențioasă, pentru că există foarte multe precauții și reguli ce trebuie urmate, pentru a asigura condițiile stricte de sterilitate și apirogenitate impuse de Farmacopeea Europeană ediția 12 și Farmacopeea Română Ediția X, fără particule vizibile, cu număr controlat de particule subvizibile, formulate astfel încât să fie izotone sau apropiate de toleranța fiziologică (când e necesar), cu pH compatibil, stabile chimic, fizic și microbiologic.

Tab. 1 Comparison between oral and injectable routes of administration

Comparison criterion	Oral route	Injectable route
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Pharmaceutical form	Film-coated tablets	Solution for injection
Route of administration	Oral	Intravenous
Absorption	Low and individually variable	Absorption is avoided because the active substance reaches the systemic circulation directly
Influence of food	Significant: foods and drinks rich in electrolytes reduce absorption	Non-existent
Bioavailability	Very low (0.6% in humans)	Virtually complete ($\approx 100\%$)
Frequency of administration	Usually monthly (150 mg once a month)	De obicei trimestrială în osteoporoză (ex. 3 mg la 3 luni)
Special conditions of administration	Requires administration in the morning, on an empty stomach, with plain water and maintaining an upright position after administration	Requires medical personnel and appropriate conditions for injection/infusion
Patient compliance	May be reduced due to strict administration rules	May be better due to less frequent and medically controlled administration
Predominant adverse reactions	Gastrointestinal disorders and esophageal irritation (esophagitis, retrosternal pain, gastralgia, nausea)	Flu-like reactions, headache, post-administration reactions
Main advantage	Non-invasive administration, convenient for home treatment	Complete bioavailability and predictable systemic effect
Main disadvantage	Low bioavailability and difficult administration	Invasive administration, requires medical supervision

Oral administration of ibandronic acid has the advantage of non-invasive and accessible use, but is limited by low bioavailability, food interactions and the risk of gastrointestinal adverse reactions. In contrast, injectable administration offers complete bioavailability, predictable systemic exposure and superior digestive tolerability, being preferable in clinical situations requiring more rigorous therapeutic control.

The recipe for preparing the acid is very simple: ibandronate sodium monohydrate, sodium chloride, glacial acetic acid, sodium acetate trihydrate, acetic acid 1% and water for injections (APPI), weighed and added in the order specified by the software linked to the preparation vessels, set to the production of this product, an initial sparging of approximately one hour with nitrogen of the APPI and shaking for a few minutes after the addition of each substance.

The installation through which the prepared solution reaches cleanliness class C (in preparation) to cleanliness class A (when filling), consists of: preparation vessel, storage vessel and filling vessel, each vessel having a pressure gauge, a vent filter and a nitrogen filter, both filters being hydrophobic. On the filter path between the preparation vessel and the storage vessel, there are two hydrophilic filters, with two different pore sizes: the first filter is 0.45 microns with a decontaminant role, and the second 0.2 microns has a sterilizing role. On the path between the storage vessel and the filling vessel, there is only a sterilizing filter. Before any filter or vent installation, they are tested - to verify their integrity, they are sterilized in an autoclave, mounted on the vessel, and after the solution transfer operations are completed, the filters are retested to certify that the solution left the preparation chamber sterile.

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The role of vent and nitrogen filters is to facilitate the transfer of the solution, under optimal sterility conditions and to limit the contact of the solution with oxygen and moisture. When the liquid is filled into a sealed vessel, the air volume must escape, otherwise overpressure occurs and the vessel or hose seals may fail. Thus, the vent allows the air to escape, but does not let microorganisms enter. When the liquid is transferred from the vessel, a vacuum can be created and it is necessary to fill the lost volume with nitrogen due to its chemically inert quality.

4. Case study on the consequences of overpressure in the syringe filling line

A situation encountered in recent practice in the case of aseptic filling of ibandronic acid syringes highlights the importance of staff training and the role of inattention. To start the actual filling, after the preparer initiates the transfer of the solution from the ST (storage tank) to the BT (filling tank), the operator must vent the sterilizing filter, opening a valve, to release the air/pressure and allow the solution to pass. The initial transfer pressure of the solution from the ST to the BT is 0.5 bar. In the case of ibandronic acid, no sterilizing filter is used during filling and there is only vent on the BT. When the solution is no longer transferred from the storage tank to the filling tank at this pressure, the preparer increases it to the pressure $p = 2$ bar and thus the path is (almost) completely emptied. Since the solution is no longer transferred from the storage vessel to the filling vessel, it was necessary to increase the pressure. Thus, in figure 1 a the functional diagram of the filtering and filling system is presented and in figure 2 b a real image of this system is presented.

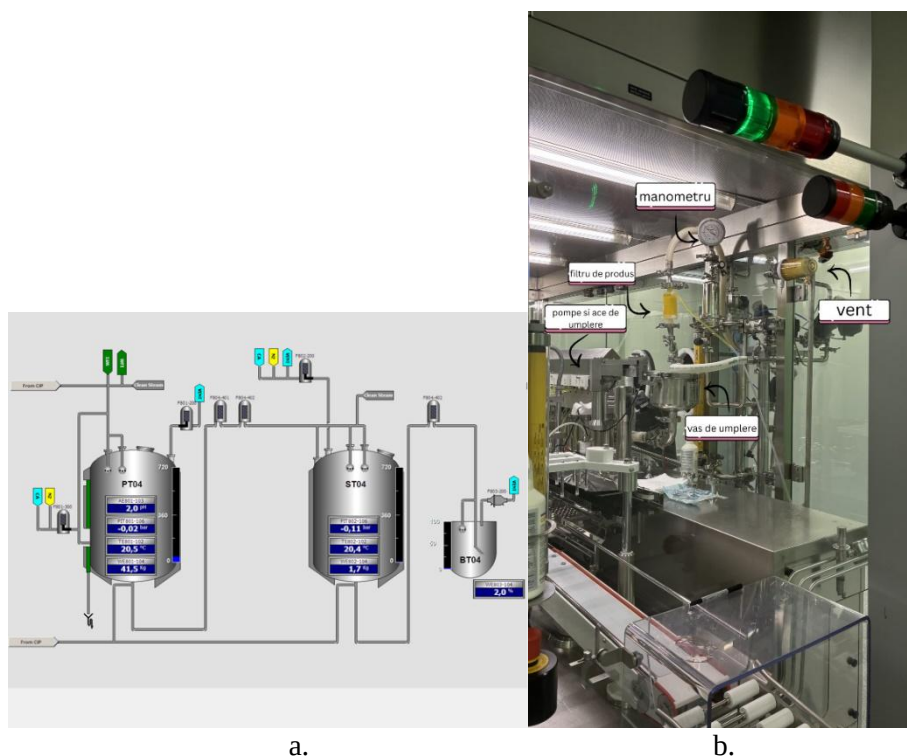


Fig. 1 presentation of the filtration-filling assembly of ibandronic acid syringes

Due to poor communication and inattention, the operator opened the valve that starts or stops the solution transfer, creating overpressure, the vessel seals failed, and the ibandronate solution

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spread onto the car windows. In this situation, two aspects must be taken into account:

- the first is that the operator should have taken into account that this product does not have a sterilizing filter when filling. Its presence would have delayed the solution transfer and would have allowed the pressure to be released gradually, through the vent valve.
- secondly, the fact that overpressure was created is due to the vent filter soaked with solution, which could not cope with the transfer, which we verified on site, by dismantling the filter and blowing it with nitrogen.

5. Occupational safety standards applicable in the parenteral preparations section

In parenteral preparation departments, occupational health and safety regulations are intended to ensure both the safety of personnel and the maintenance of aseptic conditions necessary for the manufacture of sterile products. These include, but are not limited to, the use of personal protective equipment, contamination control, pressure equipment regulations, ergonomics and fatigue prevention regulations, safe handling of chemicals, and training in compliance with GMP and SSM procedures. In critical aseptic areas, especially in GMP classes A and B, gowning is performed according to strict procedures to reduce the release of particles and microorganisms from the operator. The clothing should be made of non-particle-generating materials and sterilized before use. This equipment includes: a pair of sterile gloves that are used throughout the entire outfit, on top of which another pair of sterile gloves is added, after completing the complete outfit and before leaving the locker room in cleanliness class C, and entering cleanliness class B, two caps for complete hair coverage, autoclaved mask, individually packaged, sterile overalls, equipped with a hood, overshoes and autoclaved safety glasses.

The correct use of PPE contributes to reducing the risk of microbiological contamination, limiting personnel exposure to active substances, some of which may be toxic, or cleaning agents, but also to maintaining aseptic conditions during the manufacturing process.

Compliance with the procedures for the use of personal protective equipment is periodically verified through training, monitoring and internal audits.

In the pharmaceutical industry, especially in the parenteral preparation sections, equipment that operates under pressure is frequently used, such as: autoclaves, preparation vessels, nitrogen lines, tanks and technological pipes. This equipment poses significant risks to personnel, such as: steam burns, accidents caused by overpressure, equipment explosion, leaks of hot gases or liquids. To prevent accidents, the legislation on occupational health and safety requires compliance with specific measures: periodic inspection of equipment, the existence of safety valves, pressure and temperature monitoring, preventive maintenance, exclusive use by trained and authorized personnel. Compliance with these rules is essential both for the protection of operators and for maintaining the integrity of the technological process and GMP conditions.

The work carried out in the parenteral preparation departments requires a high level of concentration, precision and compliance with aseptic techniques. Operators often work for long periods in uncomfortable positions, wearing full protective equipment and performing repetitive tasks. These conditions can promote physical fatigue, heat stress, decreased attention, the occurrence of human errors and musculoskeletal disorders. In the aseptic environment, operator fatigue can have important consequences not only on their health, but also on the quality of the product, since human errors are one of the main sources of contamination. Several measures are applied to reduce ergonomic risks: organizing staff rotation, limiting time spent in critical areas, introducing regular breaks, training on correct working positions, ergonomic

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design of stations and equipment. At the same time, the automation of certain operations and the use of isolators contribute to reducing physical effort and operator exposure in sterile areas. Ergonomics and fatigue management is another important element for both personnel safety and for maintaining GMP compliance and finished product quality.

Personnel training is one of the fundamental requirements of both GMP standards and occupational health and safety legislation. In the production of parenteral preparations, the level of personnel training has a direct impact on product quality and the safety of the manufacturing process. Personnel must be trained before starting work and periodically thereafter, as well as whenever: changes to the technological process, new equipment, updates to procedures, legislative changes occur. Training includes both theoretical and practical aspects, relating to: GMP rules, aseptic techniques, use of personal protective equipment, hygiene and gowning procedures, handling of chemicals, operation of equipment, accident prevention, emergency response measures.

In sterile wards, staff must periodically demonstrate practical competence in aseptic technique, as inappropriate behavior can be a major source of contamination.

6. Other accidents that occurred while working in a pharmaceutical factory

Although the activities carried out in the pharmaceutical sector are strictly regulated and organized in such a way as to minimize the risks for operators and for the products intended for administration to patients, events that endanger both the safety of personnel and the quality of the manufactured medicines can occur, for various reasons. These incidents can include microbiological contamination of products, exposure of employees to toxic or carcinogenic substances, mechanical accidents caused by industrial equipment, as well as major events, such as fires and explosions.

According to studies carried out by Maaz S. Maniar and his collaborators, most serious industrial accidents in the pharmaceutical sector have been reported on the Asian continent, especially in India and China, where the high pace of production and industrial conditions can favor the occurrence of incidents such as explosions, fires or leaks of hazardous substances. These accidents are often associated with the improper handling of flammable solvents, insufficient maintenance of facilities or failure to comply with safety procedures.

Explosions are some of the most severe events that can occur in a pharmaceutical factory. These can be caused by electrical short circuits, the accumulation of flammable vapors, sparks produced by static electricity or the failure of technological equipment. In certain situations, even a low concentration of fine pharmaceutical powders can generate a risk of explosion in contact with an ignition source. In addition to the destruction produced at the factory level, such incidents can also affect the environment or nearby communities.

Another important risk is represented by accidental leaks of gases or toxic chemicals. The pharmaceutical industry uses numerous hazardous substances, such as ethylene oxide, methylene chloride, phosgene or chlorine, which can cause severe poisoning, chemical burns or respiratory damage. Also, the use of nitrogen in certain technological processes can lead to a decrease in the concentration of oxygen in rooms and the risk of asphyxiation, especially in closed and insufficiently ventilated spaces.

In addition to chemical accidents and industrial fires, pharmaceutical factories can also experience common work accidents, such as slips, falls, electrocutions or injuries caused by operating machinery. These events are favored by operator fatigue, inattention, insufficient training or failure to comply with personal protective equipment. The consequences of accidents in the pharmaceutical industry can range from minor injuries and hospitalizations to

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loss of life, damage to infrastructure and contamination of the environment. For this reason, compliance with occupational health and safety regulations, regular training and permanent monitoring of technological processes are essential measures to prevent accidents and maintain a safe working environment.

7. Conclusions

The pharmaceutical industry, especially the sterile parenteral preparations sector, is one of the most complex and strictly regulated industrial sectors, since any deviation from manufacturing conditions can have direct consequences both for the health of operators and for the safety of the patient. In this paper, the main features of the production of parenteral preparations were presented, with emphasis on the risks associated with the operation of pressure equipment and the importance of compliance with GMP and SSM standards in preventing work accidents and contamination of pharmaceutical products.

The case study on the occurrence of overpressure during the transfer of ibandronic acid solution demonstrated that, although technological processes are largely automated and controlled, the human factor remains an essential component in the conduct of production activities. A simple communication error or inattention can lead to incidents that affect both the technological process and the safety of personnel. In the analyzed situation, the consequences were limited due to the relatively low pressure and volume of the system, but the event highlights the need to strictly comply with operational procedures and to permanently verify equipment and working parameters.

Following the analyzed incident, additional prevention measures were implemented to reduce the risk of such a situation recurring. Thus, the increase in filtration pressure is no longer done suddenly, but progressively, in successive stages, from 0.5 bar to 1 bar, then to 1.5 bar and subsequently to 2 bar. This procedural change allows the gradual stabilization of the pressure in the system, reducing the stress on the seals, filters and technological route and increasing the safety level of the sterile solution transfer process.

The paper also highlights the importance of continuous personnel training, the correct use of personal protective equipment and the implementation of effective measures to prevent industrial accidents. Workplace ergonomics, operator fatigue monitoring and preventive maintenance of facilities are essential factors for reducing the risk of human error and for maintaining the aseptic conditions necessary for the production of sterile preparations.

At the same time, the analysis of serious accidents reported in the pharmaceutical industry at international level demonstrates that the risks associated with explosions, fires or leaks of toxic substances should not be underestimated. These events can have severe consequences for personnel, infrastructure and the environment, which is why risk management must be a permanent priority in any pharmaceutical production unit.

In conclusion, safety in a pharmaceutical factory depends on the interaction between the technology used, compliance with GMP and SSM regulations, the quality of staff training and an organizational culture oriented towards prevention. The continuous development of automated systems, monitoring technologies and risk management strategies can significantly contribute to reducing accidents and increasing the safety of pharmaceutical manufacturing processes.

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Simulation analysis of worker evacuation dynamics in the event of a fire in the electric vehicle industry

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ABSTRACT: *The transition to electric vehicle production introduces major industrial risks associated with lithium-ion batteries. Using the PyroSim and Pathfinder platforms, this study models the dynamics of a factory fire and its impact on evacuation by analyzing two scenarios: one involving a free-flow evacuation and the other a phased evacuation. The comparative analysis demonstrates that spontaneous evacuation generates critical bottlenecks with densities of 3 people/m² due to crowding at the exits. In contrast, implementing a phased evacuation protocol streamlines the evacuation process and reduces the total time to exit the building by 13.71%.*

KEYWORDS: simulation, evacuation, fire, electric vehicles, industry

1. Introduction

The automotive industry's transition to electromobility represents a major technological milestone, driven by the need to reduce pollutant emissions [1]. To support the large-scale production of electric vehicles, the industry has developed high-capacity production facilities focused on manufacturing lithium-ion battery packs, the central component of this new architecture [2].

This technological advancement introduces major safety risks. Lithium-ion batteries are a highly reactive medium, vulnerable to mechanical and thermal stress, factors that trigger thermal runaway [3]. The resulting fire is extremely aggressive and self-sustaining, drastically limiting the effectiveness of conventional firefighting methods. At the same time, massive emissions of highly toxic gases (particularly HF and POF₃) and the rapid spread of smoke significantly reduce survival time in enclosed spaces [4,5]. In this context, this paper aims to model the dynamics of an electric vehicle fire in an industrial hall and to evaluate the impact of these emissions on the efficiency of the evacuation process.

The methodology focuses on predictive fire assessment using the heat release rate (HRR) curve. Using the PyroSim software, 3D simulations of heat and smoke propagation are performed, highlighting the rapid deterioration of safety conditions along evacuation routes. Complementarily, occupant behavior in emergency conditions is modeled using the Pathfinder platform. This analysis allows for the identification of congestion points and the determination of the total time required to evacuate the industrial hall, thereby testing the effectiveness of evacuation strategies before people are critically exposed to toxic gases.

Given that the extremely rapid progression of an electric vehicle fire can block escape routes with toxic smoke in a short period of time, a major objective of the research is to highlight the fundamental role of advanced computer simulations. These tools are essential not only for the theoretical validation of industrial objectives, but especially for the design, testing, and practical implementation of proactive evacuation strategies, the only ones capable of preventing occupants from being caught off guard by the rapid spread of smoke and toxic gases.

2. Risks specific to the production of electric vehicles

The transition to electric vehicle assembly is fundamentally changing the risk profile of industrial facilities. Unlike traditional automotive production, where hazards associated with liquid fuels predominate, electric vehicle assembly introduces major chemical and electrical vulnerabilities. These stem from the chemistry of lithium-ion cells and the high-voltage

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architecture, with the battery pack representing the primary thermal load (the chemical “fuel”) capable of sustaining an extremely violent fire.

The safety and integrity of storage systems are directly affected by thermal and mechanical stress, with the main vulnerabilities manifesting themselves as follows:

- Exposure to high temperatures: This promotes the initiation of exothermic chemical reactions inside the cells. Due to the battery’s limited ability to dissipate heat, thermal runaway occurs, which inevitably leads to the battery pack catching fire [6].
- Exposure to low temperatures: This exponentially increases the internal resistance of the cells. The critical risk arises during charging, when the formation of lithium dendrites is encouraged. These sharp structures can pierce the separator layer, causing internal short circuits and sudden battery self-ignition.
- Mechanical impact: This poses a major operational risk in the production line due to the handling of heavy packages. Any physical impact that exceeds the casing’s strength and penetrates the cells causes immediate internal short circuits, triggering a violent fire [7].
- Thermal runaway: This involves an uncontrollable cascade of exothermic reactions, characterized by a rapid rate of heating (over 10 °C/min) and massive gas release (off gassing). Fire manifests aggressively through smoke, sparks, and flames, posing an extreme risk due to chain propagation to adjacent cells (thermal propagation).
- The danger of toxic gases and smoke: At temperatures above 150 °C, overheating causes safety valves to rupture and the sudden release of a lethal mixture of carbon monoxide (CO), hydrogen cyanide (HCN), and hydrogen fluoride (HF). Additionally, the thermal degradation of fluorinated elements in the battery generates phosphorus oxofluoride (POF₃), a compound with even higher toxicity than HF, the inhalation of which drastically reduces survival time [8,9].

3. Human behavior in emergency situations

In fire safety design, anticipating human behavior is just as important as analyzing fire dynamics. The social psychology of evacuation shows that occupants frequently exhibit atypical reactions that hinder a rapid evacuation. Among these actions that cause critical delays are initially ignoring the alarm while waiting for confirmation of the danger, moving toward the source of the fire to investigate the situation directly, warning colleagues and forming groups, gathering personal belongings, or even staff attempting to extinguish the fire using first-response equipment [10]. Additionally, the tendency of most people to use only familiar routes (such as the main door) and to ignore alternative emergency exits is a decision that quickly leads to severe bottlenecks in the evacuation flow.

Although widespread panic is a rare occurrence, the rapid deterioration of environmental conditions (accumulation of toxic smoke, reduced visibility, and extreme heat) triggers episodes of acute stress. During these critical phases, behavior deteriorates, with occupants exhibiting confusion and disorientation due to a loss of spatial orientation. Extreme stress promotes irrational decisions (disregarding safety, forcing blocked exits) and the emergence of the “herd effect,” a high-risk situation in which individuals instinctively follow the crowd without rationally assessing whether the chosen evacuation route is truly safe [11].

4. Methodology for the mathematical modeling of evacuation scenarios

The computational analysis focused on an industrial building used for the production of electric vehicles (one production floor and two administrative floors). The initial geometry was defined in 2D in AutoCAD, serving as the basis for 3D modeling in the Thunderhead Engineering suite [12].

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To simulate an electric vehicle fire, the energy profile was defined using the HRR (Heat Release Rate) parameter with a value of 32,000 kW, whose evolution over time is shown in Figure 1.

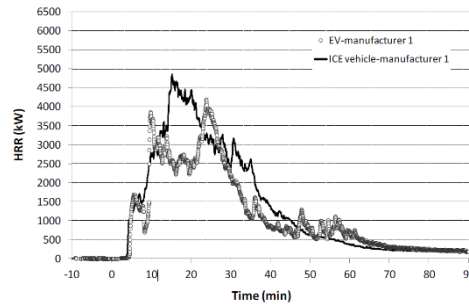


Fig. 1 Heat release rate for an electric vehicle fire [13]

PyroSim was used to construct the 3D model (Figures 2a and 2b) and simulate the fire, while Pathfinder was used to model crowd dynamics and estimate evacuation times.

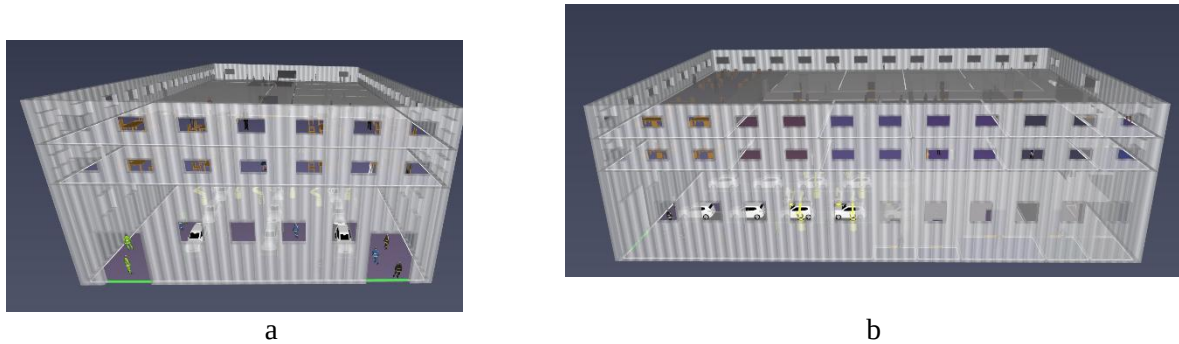


Fig. 2 3D representation of industrial space

Two complementary scenarios were defined in the Pathfinder platform for the evacuation of 140 occupants, distributed across production and administrative areas. The modeling involved assigning physical and behavioral profiles specific to emergency situations (Figure 3).

- ⊕ 🧑 Evacuarea cea mai apropiată
- ⊕ 🧑 Evacuare cunoscută stânga
- ⊕ 🧑 Evacuarea cunoscută dreapta
- ⊕ 🧑 Schimbare direcție spre dreapta
- ⊕ 🧑 Schimbare direcție spre stânga
- ☐ 🧑 Confuzie
- 🚩 Goto (1,9, 13,6, 9,0) m
- ⌚ Wait (1,5 s)
- 🚩 Goto (2,4, 18,9, 9,0) m
- 🚩 Goto Stanga - 9 m
- EXIT Exit <any>
- ☐ 🧑 Panică
- 🚩 Goto (1,9, 13,6, 9,0) m
- ⌚ Wait (6,0 s)
- EXIT Exit <any>
- ⊕ 🧑 Blocaj scări stânga
- ⊕ 🧑 Evacuare întârziată
- ⊕ 🧑 Blocaj scări dreapta
- ⊕ 🧑 Evacuare stanga etaj 2
- ⊕ 🧑 Evacuare dreapta etaj 2
- ⊕ 🧑 Așteptare coadă și răzgândire

Fig. 3 Illustrating behaviors specific to an emergency situation

Un Another key parameter in defining occupant profiles is travel speed. This was determined based on the characteristics of the travel surface, with separate values established for horizontal movement (Table 1) and vertical movement (Table 2).

Table 1. Horizontal travel speed

Age	Gender	Travel speed [m/s]
under 29 years old	M	1,77
under 29 years old	F	1,64

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30–50 years old	M	1,87
30–50 years old	F	1,75
50 years of age and older	M	1,42
50 years of age and older	F	1,35

Table 2. Speed of movement on stairs

Age	Gender	Travel speed [m/s]
under 29 years old	M	0,82
under 29 years old	F	0,59
30–50 years old	M	0,69
30–50 years old	F	0,50
50 years of age and older	M	0,56
50 years of age and older	F	0,47

To provide a detailed representation of the industrial space, 3D objects created in SketchUp were integrated (Figures 4a and 4b). These are intended to accurately reproduce the electric vehicle production environment and realistically depict the obstacles present in the evacuation routes, such as robotic arms or vehicles on the assembly line.

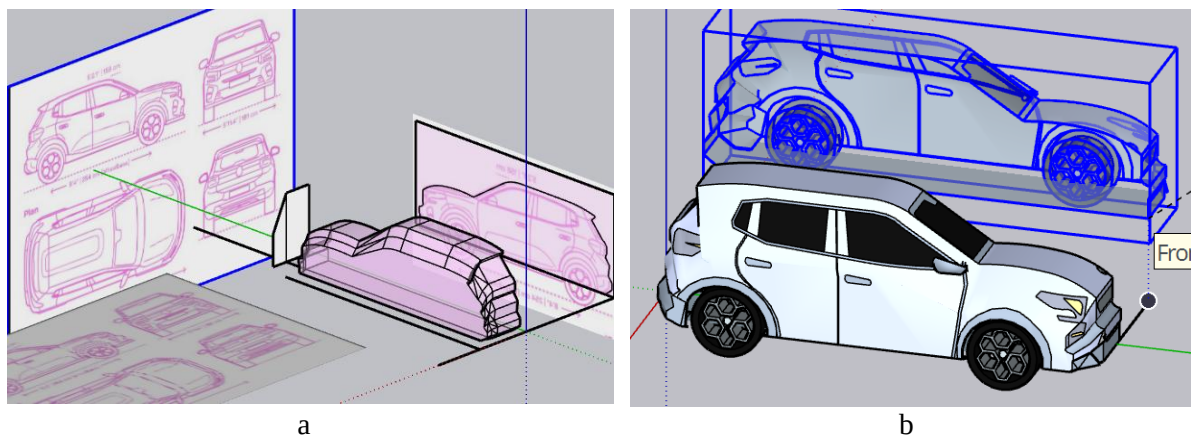


Fig. 4 The process of geometric modeling of an electric vehicle

5. Scenario analysis and interpretation of results

The comparative analysis evaluated two evacuation scenarios. The first scenario simulates an uncontrolled evacuation, in which all occupants react simultaneously to a fire breaking out on the production line, with their actions based exclusively on predefined emergency response protocols.

For the second scenario, a 25-second delay in evacuation was proposed for occupants on the top floor, as well as an approximately equal distribution of occupants across the two evacuation routes.

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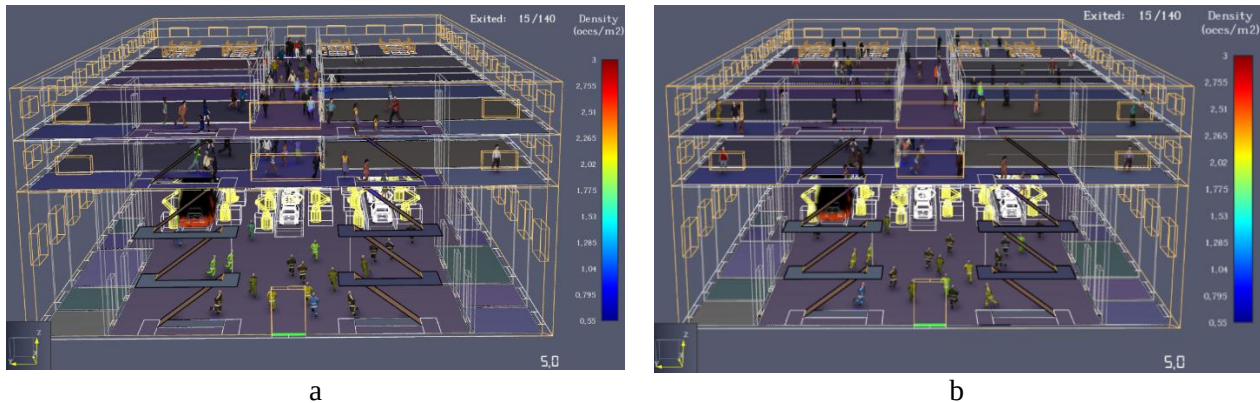


Fig. 5 Illustration of the evacuation process after 5 seconds for Scenario 1 (a) and Scenario 2 (b)

Within the first 5 seconds of the evacuation alarm sounding, 15 employees on the ground floor managed to leave the production hall, while staff in the administrative area began moving toward the stairwell. The behavioral differences are significant; in the absence of a protocol (Figure 5a), occupants move simultaneously and in an uncontrolled manner toward the stairwells, with isolated instances of confusion (right wing, 2nd floor). In contrast, the phased scenario (Figure 5b) demonstrates strict adherence to the procedure, with staff on the top floor remaining stationary during the required delay.

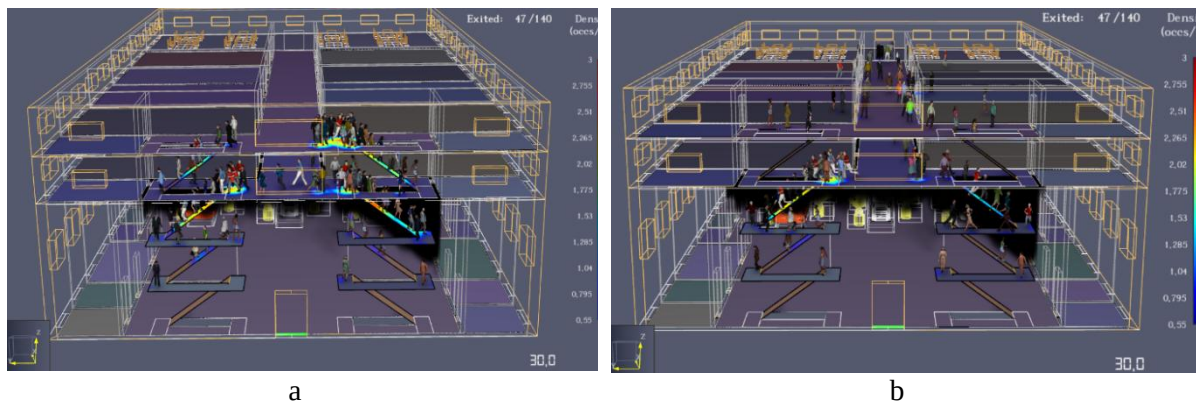
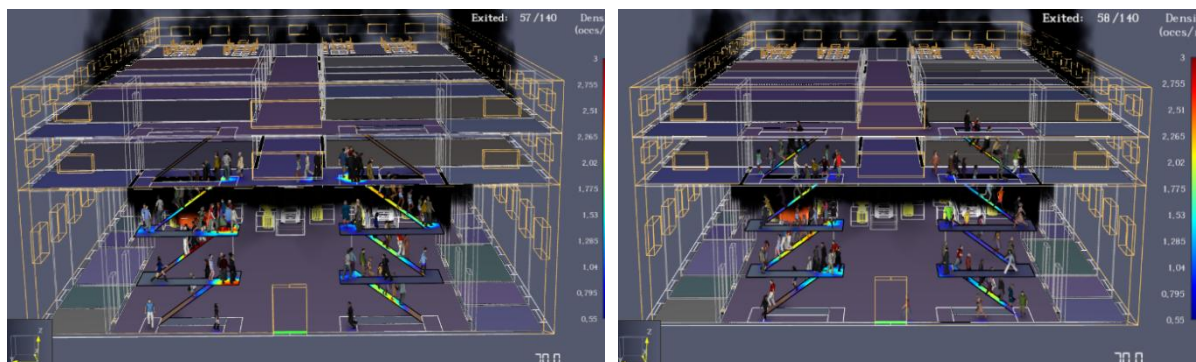


Fig. 6 Illustration of the evacuation process after 30 seconds for Scenario 1 (a) and Scenario 2 (b)

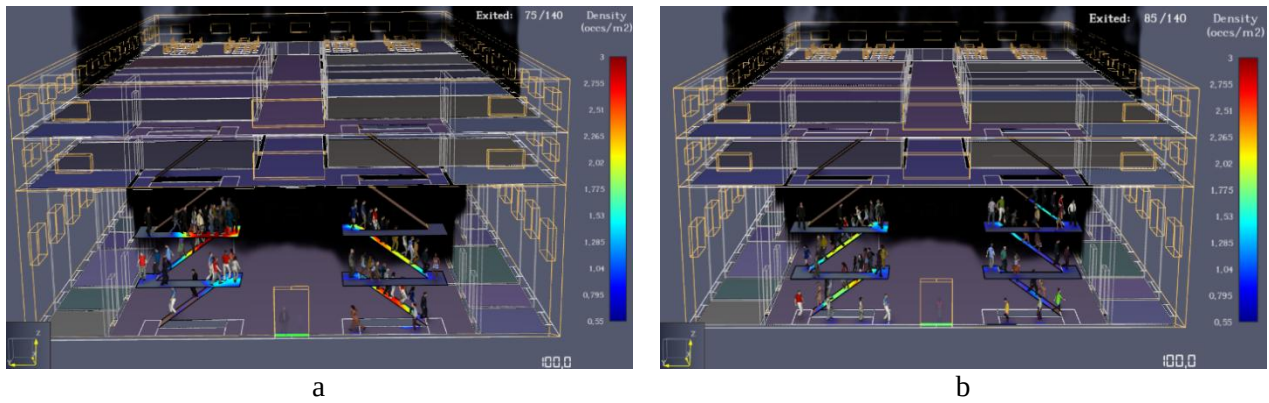
During the first 30 seconds of the simulation, uncontrolled evacuation (Figure 6a) leads to a series of bottlenecks that hinder the process, congested areas marked by a density of approximately 2 people/m² on both staircases, and hesitation and confusion observed among occupants in the intermediate zone between the two evacuation routes. In the phased scenario (Figure 6b), people on the second floor began the evacuation process 5 seconds earlier, and the movement of personnel from the first-floor proceeds without blockages.



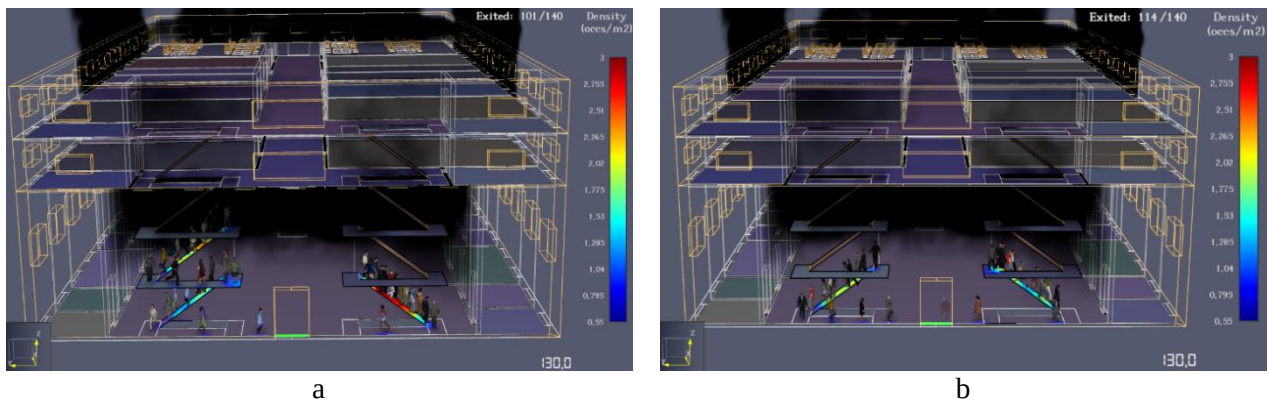
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a b
Fig. 7 Illustration of the evacuation process after 70 seconds for Scenario 1 (a) and Scenario 2 (b)

After 70 seconds, in the case of spontaneous evacuation (Figure 7a), even though the second floor is completely cleared, crowding and hesitant behavior (such as people changing their minds on the first floor) contribute to the persistence of congestion points, where critical densities of 2–3 people/m² are recorded, thereby slowing the evacuation process for all remaining occupants. In contrast, the phased scenario (Figure 7b) demonstrates its effectiveness by maintaining a stable flow, characterized by a much lower and constant density of 1–2 people/m².



a b
Fig. 8 Illustration of the evacuation process after 100 seconds for Scenario 1 (a) and Scenario 2 (b)
After 100 seconds, in the case of an uncontrolled evacuation (Figure 8a), even if the movement takes place entirely on the lower level of the building, congestion points caused by human bottlenecks persist, which prolongs the occupants' stay in the stairwell area space already filled with toxic smoke. In contrast, the phased evacuation scenario (Figure 8b) illustrates a smoother flow of movement and a much faster process, showing a total of 85 people evacuated, compared to the first scenario, which recorded only 75. Thus, occupants no longer become stuck on the evacuation routes, and individual exposure to extreme conditions is reduced.



a b
Fig. 9 Illustration of the evacuation process after 130 seconds for Scenario 1 (a) and Scenario 2 (b)
The scene captured at 130 seconds into the simulation, spontaneous evacuation (Figure 9a), results in congestion at the base of the stairwells, with densities reaching the maximum threshold of 3 people/m², thereby blocking the exit of the last groups, who remain exposed to high temperatures and smoke concentrations. In contrast, the phased evacuation strategy

Simulation analysis of worker evacuation dynamics in the event of a fire in the electric vehicle industry

ensures a much more uniform movement, with a density of one person/m² and a greater number of people who managed to evacuate safely.

Through the phased evacuation process, people on the top floor spend much less time in the building-exit phase, which eliminates the overlap of occupant flows and prevents bottlenecks from forming in the stairwells.

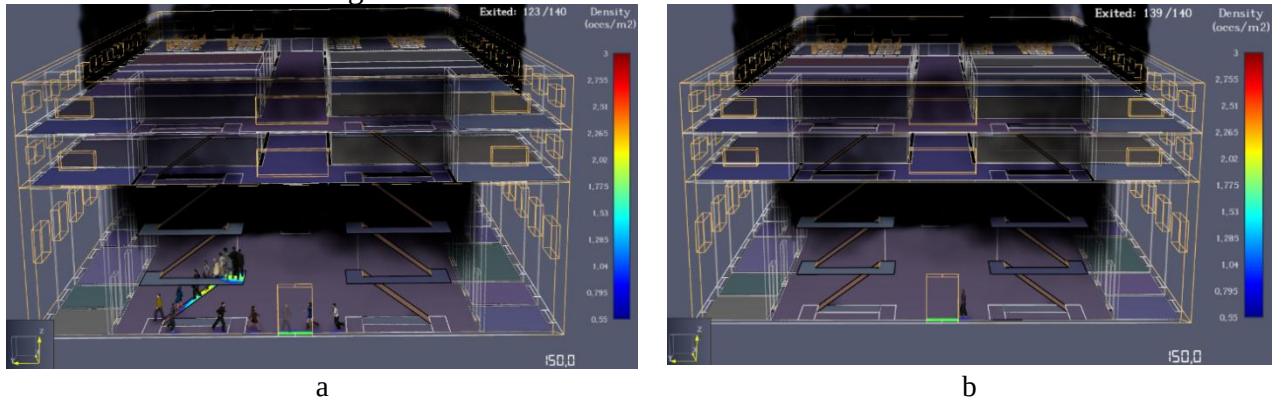


Fig. 10 Illustration of the evacuation process after 150 seconds for Scenario 1 (a) and Scenario 2 (b)

The moment marked by the 150-second mark represents a defining point in the comparative analysis of the two scenarios. In the case of the uncontrolled evacuation (Figure 10a), the total number of people brought to safety is 123, with the remaining group of 17 people still trapped on the stairs. The total evacuation time for this scenario is 175 seconds. In contrast, the phased evacuation scenario (Figure 10b) marks the end of the rescue process, showing a complete evacuation of the production hall.

6. Conclusions

A comparative analysis of the two scenarios demonstrates that implementing a dynamic phased evacuation strategy is a technically superior solution to traditional emergency procedures, with a direct impact on the building's occupants. While a spontaneous evacuation resulted in severe congestion in the stairwell (caused by confusion and second thoughts, reaching densities of up to 3 people/m²), the strategy based on an organized evacuation protocol allowed for a noticeable smoothing of the flow of people.

The main difference between the two simulations lies in the implementation of a pre-evacuation period (phasing) in Scenario 2. Although the specific behaviors associated with the alarm states remained similar, the frequency of their occurrence produced different effects. In the case of an uncontrolled evacuation, crowding persists throughout the movement, because of stops and sudden changes in direction. In contrast, the time lag in the phased scenario provides occupants who were initially at rest with a period of anticipation, minimizing irrational reactions and facilitating superior self-organization among individuals during the movement process.

Another key factor affecting evacuation times is the vertical movement dynamics. This is determined by the occupants at the front of the flow, who move at a reduced speed (0.47 m/s). Delays are exacerbated by the spatial constraints of the stairwell, where the ability to pass others is limited, forcing each person to match the pace of those in front.

The fire propagation analysis demonstrated an extremely rapid progression, with uncontrolled releases of hot and toxic gases occurring in less than 3 minutes. The 90th second of the simulation marks the critical moment when the conditions for sustainable fire growth were disrupted by the rapid infiltration of smoke into the stairwell. In the spontaneous evacuation scenario, congestion points and slow movement speeds result in prolonged delays

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in the stairwell, exposing occupants to rising toxic concentrations. In contrast, the phased scenario demonstrates a clear improvement in efficiency through the streamlining of movement, which resulted in a 13.71% reduction in total evacuation time, a performance equivalent to saving a group of 17 people.

The progression and severe toxicity of the fire highlight the critical vulnerabilities of industrial environments where Li-Ion batteries are handled, underscoring the need for minimum response time and precise organization. These requirements can be met through a specific emergency plan, in which establishing response times, designating available routes, and managing traffic flows are central elements.

Ultimately, advanced modeling platforms such as PyroSim and Pathfinder have proven to be essential tools for fire safety engineering. In the context of this research, they provided a vital predictive insight into a fire that broke out in an electric vehicle manufacturing facility. These tools enabled the precise modeling of the three-dimensional geometry of the industrial space, the definition of fire dynamics parameters, and the individual behavior of occupants, based on psychological factors such as irrational reactions (confusion and panic) and the search for familiar routes (rethinking), as well as biometric data (age and gender). The importance of these simulations lies in their ability to generate scenarios that allow for the anticipation of congestion points and areas with hazardous survival conditions before they manifest in a real-world situation. Thus, design specialists can validate evacuation strategies, optimizing building architecture and emergency protocols to ensure a rapid, safe evacuation process for all occupants within an optimal timeframe.

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INTELLIGENT VENTILATION SYSTEMS FOR INDUSTRIAL HALLS

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This paper presents the design and implementation of an automated ventilation system for industrial environments, controlled via a Raspberry Pi 3 B. The project focuses on air quality monitoring and active safety through a series of intelligent scenarios, including fan redundancy and emergency response to fire or high gas concentrations.

Using of MQ-135, MQ-2, and GP2Y1010 and bmp280 sensors, the system evaluates the internal environment in real-time. A key feature of the proposed architecture is the "fail-safe" logic, where the failure of one intake fan triggers the automatic speed compensation of the remaining units. The hardware is integrated into an L-shaped scale model, demonstrating practical industrial automation and human-safe environmental control.

1. Introduction

Ventilation in industrial spaces is not just a matter of comfort, but a critical safety element. An accumulation of toxic gases or a fire can have devastating consequences if the evacuation system does not react instantaneously. The present project proposes a modern automation solution, built around a Raspberry Pi microcomputer. The main objective was to create a system that is not just "passive" but capable of "active reduction". This means that if a fan malfunctions, the system detects the problem and forces the remaining fans to compensate for the lost airflow. Everything is monitored by smoke, particulate, and temperature sensors, providing an accurate simulation of an industrial hall.

2. Current State

The system mockup was built in the shape of an "L-shaped" hall, covered with plexiglass to allow the observation of the components during testing. We opted for a configuration with 7 compact 50 mm fans, as they offer an ideal ratio between size and realism for a university mockup. The system is divided into three functional zones:

- Intake: 3 fans introducing fresh air;
- Ceiling Exhaust: 2 fans operating continuously;
- Emergency: 2 additional fans that activate only in case of fire or severe contamination.

3. System Architecture and Connectivity

For power control, considering that the Raspberry Pi operates at 3.3V, we used 3 IRF520 MOSFET modules. These allow PWM (Pulse Width Modulation) control of the fans powered by a 12V external power supply, without overloading the development board. The sensors used are:

- DHT22 for temperature and humidity monitoring;
- MQ-135 and MQ-2 for air quality and smoke/gas detection;
- GP2Y1010, an optical sensor for dust and fine particles;

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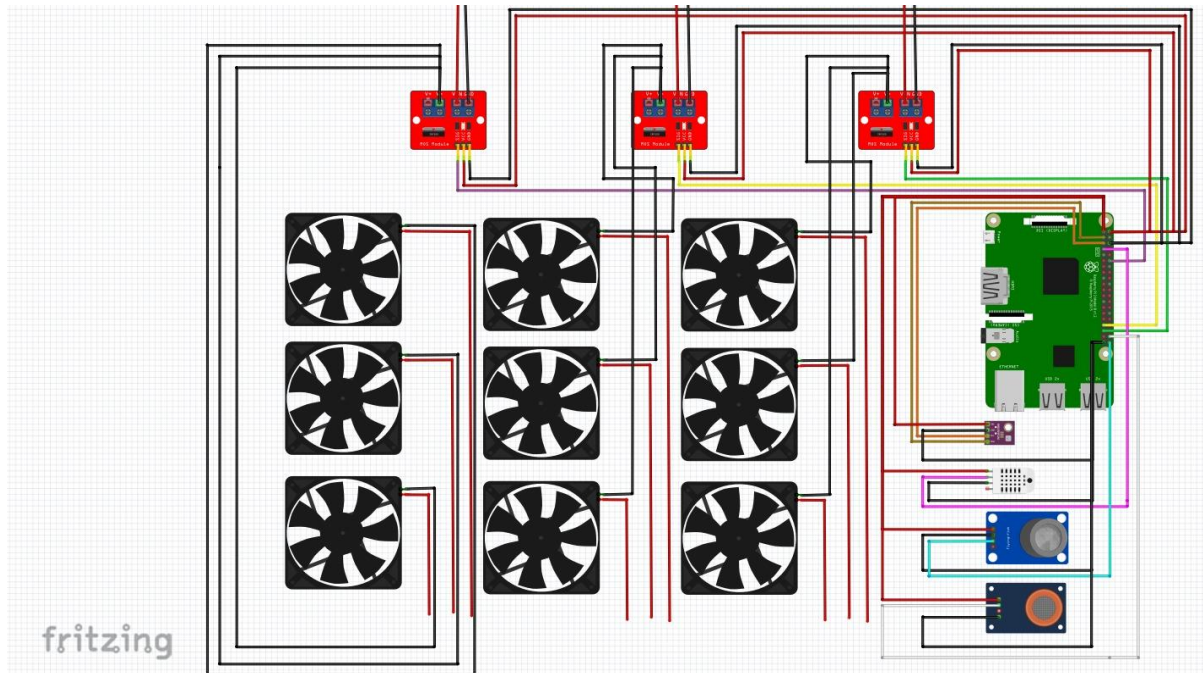


Diagram created in Fritzing software

Below is the code for the entire project, written in Python 3:

```
import RPi.GPIO as GPIO
import time
import board
import busio
import adafruit_bme280
GPIO.setmode(GPIO.BCM)
FAN_INTAKE = 18
FAN_EXHAUST = 19
FAN_EMERGENCY = 13
BTN_FAILURE = 17
BTN_FIRE = 27
BTN_GAS = 22
BUZZER = 23
GPIO.setup(FAN_INTAKE, GPIO.OUT)
GPIO.setup(FAN_EXHAUST, GPIO.OUT)
GPIO.setup(FAN_EMERGENCY, GPIO.OUT)
GPIO.setup(BUZZER, GPIO.OUT)
GPIO.setup(BTN_FAILURE, GPIO.IN, pull_up_down=GPIO.PUD_UP)
GPIO.setup(BTN_FIRE, GPIO.IN, pull_up_down=GPIO.PUD_UP)
GPIO.setup(BTN_GAS, GPIO.IN, pull_up_down=GPIO.PUD_UP)
pwm_intake = GPIO.PWM(FAN_INTAKE, 1000)
pwm_exhaust = GPIO.PWM(FAN_EXHAUST, 1000)
pwm_emergency = GPIO.PWM(FAN_EMERGENCY, 1000)
pwm_intake.start(0)
pwm_exhaust.start(0)
pwm_emergency.start(0)
i2c = busio.I2C(board.SCL, board.SDA)
bme280 = adafruit_bme280.Adafruit_BME280_I2C(i2c)
def normal_mode():
    pwm_intake.ChangeDutyCycle(45)
    pwm_exhaust.ChangeDutyCycle(55)
    pwm_emergency.ChangeDutyCycle(0)
    GPIO.output(BUZZER, GPIO.LOW)
def failure_mode():
    pwm_intake.ChangeDutyCycle(90)
    pwm_exhaust.ChangeDutyCycle(55)
```

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```
def fire_mode():
    pwm_intake.ChangeDutyCycle(100)
    pwm_exhaust.ChangeDutyCycle(100)
    pwm_emergency.ChangeDutyCycle(100)
    GPIO.output(BUZZER, GPIO.HIGH)
def gas_mode():
    pwm_intake.ChangeDutyCycle(85)
    pwm_exhaust.ChangeDutyCycle(85)
    pwm_emergency.ChangeDutyCycle(40)
try:
    while True:
        temperature = bme280.temperature
        humidity = bme280.humidity
        print(f"Temp: {temperature:.1f} C")
        print(f"Humidity: {humidity:.1f} %")
        normal_mode()
        if temperature > 32:
            pwm_intake.ChangeDutyCycle(80)
            pwm_exhaust.ChangeDutyCycle(85)
        if GPIO.input(BTN_FAILURE) == 0:
            print("Defect ventilator detectat")
            failure_mode()
            time.sleep(3)
        if GPIO.input(BTN_FIRE) == 0:
            print("ALERTA INCENDIU")
            fire_mode()
            time.sleep(5)
        if GPIO.input(BTN_GAS) == 0:
            print("Contaminare aer detectata")
            gas_mode()
            time.sleep(5)
        time.sleep(1)
except KeyboardInterrupt:
    print("Sistem oprit")
finally:
    pwm_intake.stop()
    pwm_exhaust.stop()
    pwm_emergency.stop()
    GPIO.cleanup()
```

4. Intelligent Scenarios and Operation

Unlike a classic ventilation system, we have implemented three critical scenarios that can be triggered manually (via buttons) or automatically (via sensors):

- Scenario 1 (Redundancy): Simulating the failure of an intake fan. Upon pressing button 1, fan 1 stops, and the system automatically increases the speed of fans 2 and 3 from 50% to 90% to maintain air pressure;
- Scenario 2 (Fire): Upon smoke detection or pressing button 2, all exhaust fans (including emergency ones) switch to 100% power, simultaneously activating an audible and visual alarm;
- Scenario 3 (Contamination): An increase in CO2 levels or toxic gases activates the rapid refresh mode, increasing both intake and exhaust until the sensor readings stabilize.

5. Conclusions

The original contributions of this paper consist of: implementing the compensation logic in case of failures; hybrid integration of analog sensors on a digital platform (Raspberry Pi); passive automation: the system reacts on its own to cigarette smoke or high temperature, without human intervention.

The project demonstrates how accessible technologies such as Raspberry Pi and the MQ sensor series can be used to create complex industrial prototypes, capable of saving lives through rapid

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automated reactions.

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EDUCATIONAL MIXED REALITY APP FOR ADDITIVE MANUFACTURING

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ABSTRACT: *This paper presents the design and development of an immersive Virtual Reality simulator for operating and calibrating Fused Deposition Modeling (FDM) 3D printers, built using the Unity 6 game engine and the Meta XR Core SDK targeting Meta Quest standalone devices. Traditional hands-on training with 3D printing equipment involves significant risks of hardware damage, material waste, and operator injury during calibration procedures. The proposed VR simulator replicates the complete operational workflow of a FDM printer — filament loading, SD card insertion, auto-homing calibration, and layer-by-layer print simulation — through natural hand interaction enabled by the Meta Interaction SDK (Grabbable, HandGrabInteractable, SnapZone components). A World Space Canvas provides contextual feedback and conditional menu navigation tied to the physical state of the simulated machine. Results demonstrate stable execution at 72 fps on Meta Quest 3S.*

KEY WORDS: *Virtual Reality, Unity 3D, 3D Printing Simulation, Meta Interaction SDK, Immersive Training.*

1. Introduction

Additive manufacturing, especially Fused Deposition Modeling (FDM) 3D printing technology, has gone beyond niche status to become a current presence in university labs, prototyping workshops, and production lines. The versatility of the process, combined with the constant reduction of equipment costs, has led to its widespread adoption as a practical training tool in technical education institutions. However, this spread raises a problem that is as common as it is neglected: the correct operation of an FDM printer requires the assimilation of precise technical procedures — calibration of the bed, loading of the filament, management of the SD card, interpretation of slicing parameters — and practicing them on real equipment entails real risks, both for the operator and for the machine.

Damage to the nozzle or the heated bed through a wrong calibration can take out of use an equipment of several thousand lei. In laboratories with a large number of students and a small number of printers, this is not only a technical problem, but an economic one.

Virtual Reality offers a structural solution in this context: an MR simulator allows unlimited practice of operational procedures, in any order, with the possibility of making mistakes without material consequences and resuming the sequence immediately. Unlike video tutorials or text documentation, immersive simulation engages the user's procedural memory through virtual physical action, significantly increasing the rate of transfer of knowledge acquired in the context of real equipment [1]. This paper presents the design, technical architecture and implementation of an MR simulator for FDM 3D printers, developed in Unity 6 and intended for standalone Meta Quest 3S devices, with a focus on the naturalness of physical interaction through the Meta Interaction SDK.

2. Current status

Virtual Reality simulation has proven its worth in areas where error in the real environment is

unacceptable — surgery, aviation, nuclear industry — and there is a substantial body of research that supports the transfer of this approach to industrial technical training. The meta-analysis by Merchant et al. (2014), carried out on 69 independent studies, confirms that interactive VR applications produce learning outcomes superior to conventional methods, with a statistically significant effect precisely for procedural and psychomotor tasks [4] — a category in which the operation of an FDM printer directly falls.

The relevance for additive manufacturing is also supported by field-specific studies. Recent research shows that immersive VR platforms can effectively teach digital manufacturing concepts and 3D printing processes, with a positive impact on learners' practical understanding and engagement, while also compensating for the wear and tear of physical equipment [3].

However, the commercial offer of VR simulators dedicated to 3D printers remains remarkably underdeveloped compared to the identified potential. Existing educational platforms focus on generic assembly procedures or conventional production processes; the FDM-specific flow — preparation, calibration, print monitoring, error management — is not systematically addressed either in the literature or in available commercial products.

From a hardware perspective, the Meta Quest 3S in standalone configuration eliminates the dependency on dedicated PC infrastructure, allowing deployment in any classroom. The Meta Interaction SDK provides pre-built components for physical interaction with virtual objects — grab, snap, poke — substantially reducing implementation complexity and letting the development effort focus on the specific logic of the simulator [1].

3. Simulator Architecture and Development

The simulator was built in Unity 6 (version 6000.0 LTS), using the Meta XR Core SDK and Meta Interaction SDK packages imported through the Unity Package Manager from the official Meta registry. The target platform is Meta Quest 3S in standalone configuration (Android ARM64), without dependence on an external PC. The architecture of the application explicitly separates three functional layers: the physical interaction layer (Grab & Snap), the user interface layer (World Space Canvas), and the cinematic simulation layer (Coroutine-driven axes), each governed by independent C# scripts that communicate through Unity events [1].

3.1. Physical Interaction Mechanics – Grab & Snap

The main interactive objects—the Filament Roll and SD Card—are configured with the Grabbable and HandGrabInteractable components of the Meta Interaction SDK. Grabbable handles the translation and rotation of the object during gripping, and HandGrabInteractable defines specific hand poses for a realistic grip, different for each individual object.

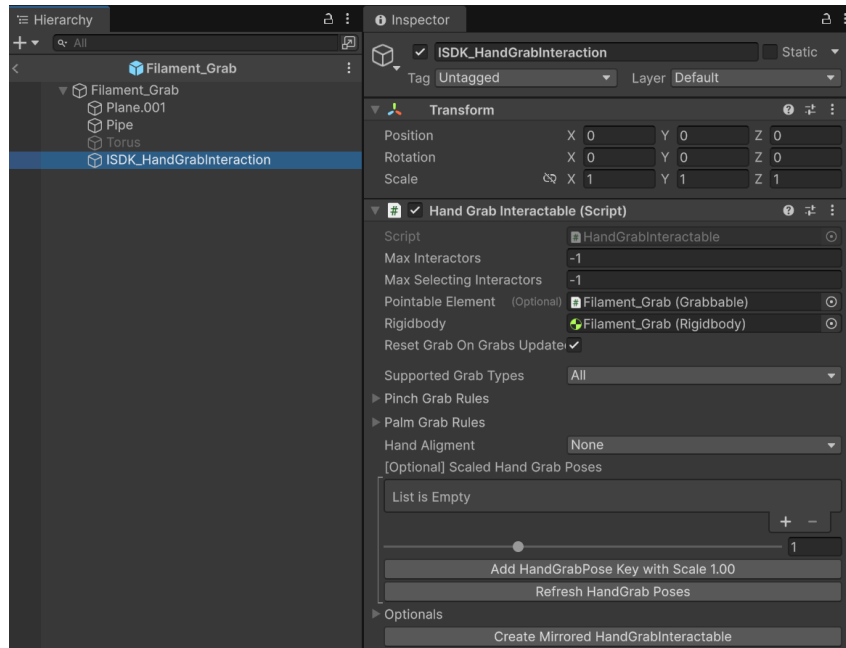


Fig. 1. Interactive Object Hierarchy in Unity 6 – Grabbable and HandGrabInteractable components configured in the Inspector

Attaching components to printer slots is handled via the Snap Interactor (on the mobile object) / SnapZone – Snap Interactable (on the printer) pair. When the object enters the range of the snap zone, the system attracts it and secures it in the exact pre-configured position, simulating physical insertion. A common problem in snap-on-grab implementations is jittering: after fixing, the conflict between the constraints of the grab physics and those of the SnapZone produces a visible vibration of the object. The solution adopted is to programmatically disable the HandGrabInteractable component at the time of triggering the WhenSelect() event of the SnapZone, simultaneously blocking the object's Rigidbody (isKinematic = true). This intervention fixes the object permanently in its slot, completely eliminating interference and ensuring a smooth visual transition.

```

172
173
174     public void SDCardWasInserted()
175     {
176         isSDCardInserted = true;
177         UpdateSecondaryMenuUI();
178
179         // Găsim clona cardului SD și oprim scripturile de apucare (Grab)
180         GameObject card = GameObject.Find("SD_Card(Clone)");
181         if (card != null)
182         {
183             MonoBehaviour[] scripturi = card.GetComponentsInChildren<MonoBehaviour>();
184             foreach (MonoBehaviour script in scripturi)
185             {
186                 if (script.GetType().Name.Contains("Grab"))
187                 {
188                     script.enabled = false;
189                 }
190             }
191         }

```

Fig. 2. C# script for controlling Snap Zone and disabling the Grab component when inserting the SD card

3.2. User Interface – World Space Canvas

The interface is implemented as a World Space Canvas anchored in the 3D space in front of the printer, with interaction achieved exclusively by virtual touch via the ISDK_PokeCanvasInteraction component — without physical controllers. The menu implements conditional paging logic: the track selection and

print initiation tab remains inaccessible until the SnapController script confirms the insertion of the SD card by setting a Boolean flag. This restriction replicates the operational fidelity of real FDM printers, on which print files cannot be accessed in the absence of a valid storage media, and simultaneously serves as the default user guide through the correct operating flow.

3.3. Printer Kinematics Simulation – Coroutines and Linear Interpolation

The movement of the printer's three mechanical axes—Z-axis (Gantry/portal), Y-axis (heated bed), X-axis (extrusion head)—is simulated by C# Routines (IEnumerator) that uses Vector3.Lerp() for linear interpolation between the start and target positions. Shortcuts allow movements to be executed asynchronously with the main thread of the graphics engine, eliminating any frame-rate jamming during animation sequences. The Auto Home procedure sequentially runs through each axis to the Home-position, with configurable times per axis. Immediately after Auto Home, when selecting the part from the menu, a second sequence of Routines simulates the printing movements layer by layer: the bed incrementally descends on Z, the extruder traverses X and the Gantry assembly advances on Y, faithfully replicating the kinematics of an FDM printer.

```
IEnumerator AutoHomeRoutineComplete() {
    isHoming = true; btnAutoHome.interactable = false;
    Vector3 bedStartPos = heatedBedTarget.localPosition;
    Vector3 gantryStartPos = gantryTarget.localPosition;
    Vector3 extruderStartPos = extruderTarget.localPosition;
    statusText.text = "Homing Gantry (Z) ...";
    float deltaTestZ = gantryTestZ - gantryStartPos.z;
    float deltaHomeZ = gantryHomeZ - gantryStartPos.z;
    Vector3 gantryTestPos = new Vector3(gantryStartPos.x, gantryStartPos.y, gantryTestZ);
    Vector3 extTestZPos = new Vector3(extruderStartPos.x, extruderStartPos.y, extruderStartPos.z + deltaTestZ);
    Vector3 gantryFinalHome = new Vector3(gantryStartPos.x, gantryStartPos.y, gantryHomeZ);
    Vector3 extHomeZPos = new Vector3(extruderStartPos.x, extruderStartPos.y, extruderStartPos.z + deltaHomeZ);
    StartCoroutine(MoveComponent(extruderTarget, extruderStartPos, extTestZPos, timpGantry));
    yield return StartCoroutine(MoveComponent(gantryTarget, gantryStartPos, gantryTestPos, timpGantry));
    yield return new WaitForSeconds(0.1f);
    StartCoroutine(MoveComponent(extruderTarget, extTestZPos, extHomeZPos, timpGantry));
    yield return StartCoroutine(MoveComponent(gantryTarget, gantryTestPos, gantryFinalHome, timpGantry));
    extruderStartPos = extruderTarget.localPosition;
    statusText.text = "Switching Axis..."; yield return new WaitForSeconds(0.3f);
    statusText.text = "Homing Bed...";
    Vector3 bedTestTarget = new Vector3(bedTestX, bedStartPos.y, bedStartPos.z);
    yield return StartCoroutine(MoveComponent(heatedBedTarget, bedStartPos, bedTestTarget, timpPat));
    yield return new WaitForSeconds(0.1f);
    yield return StartCoroutine(MoveComponent(heatedBedTarget, heatedBedTarget.localPosition, bedStartPos, timpPat));
    statusText.text = "Switching Axis..."; yield return new WaitForSeconds(0.3f);
    statusText.text = "Homing Extruder...";
    Vector3 extTest1 = new Vector3(extruderStartPos.x, extruderTestY_1, extruderStartPos.z);
    Vector3 extTest2 = new Vector3(extruderStartPos.x, extruderTestY_2, extruderStartPos.z);
    Vector3 extHome = new Vector3(extruderStartPos.x, extruderHomeY, extruderStartPos.z);
    yield return StartCoroutine(MoveComponent(extruderTarget, extruderStartPos, extTest1, timpExtruder));
    yield return new WaitForSeconds(0.1f);
    yield return StartCoroutine(MoveComponent(extruderTarget, extruderTarget.localPosition, extTest2, timpExtruder));
    yield return new WaitForSeconds(0.1f);
    yield return StartCoroutine(MoveComponent(extruderTarget, extruderTarget.localPosition, extHome, timpExtruder));
    statusText.text = "Auto Home Complete"; isHoming = false; btnAutoHome.interactable = true;
}
```

Fig. 3. Simulation of the kinematic motion of the 3D printer axes by Corrutine (IEnumerator) and Vector3.Lerp

4. Results and Discussions

The simulator fully reproduces the operational flow of a user starting an FDM 3D printer for the first time. The experience is structured in seven successive stages, each conditioned by the correct completion of the previous one: (1) picking up and inserting the Filament Roll in the dedicated slot; (2) automatic spawning of the SD Card in the field of view; (3) inserting the SD Card, which unlocks the print menu; (4) selection of the desired part from the catalog; (5) the automatic execution of the Auto Home procedure; (6) simulation of layer-by-layer printing, with the gradual appearance of the piece on the bed through the Y-axis controlled clipping technique, synchronized with a progress bar in the Canvas; (7) programmatically activating the Grabbable component on the finished part, allowing it to be harvested from the printer bed.

The technique of gradual appearance of the piece deserves a separate mention. The 3D part has been on the scene since the beginning of printing, but it is progressively cut through a clipping shader on the Y-axis — as the progress bar advances, the clipping limit rises, giving the impression that the part is growing layer by layer. The effect is convincingly visually and computationally inexpensive, without

requiring procedural geometry generation.

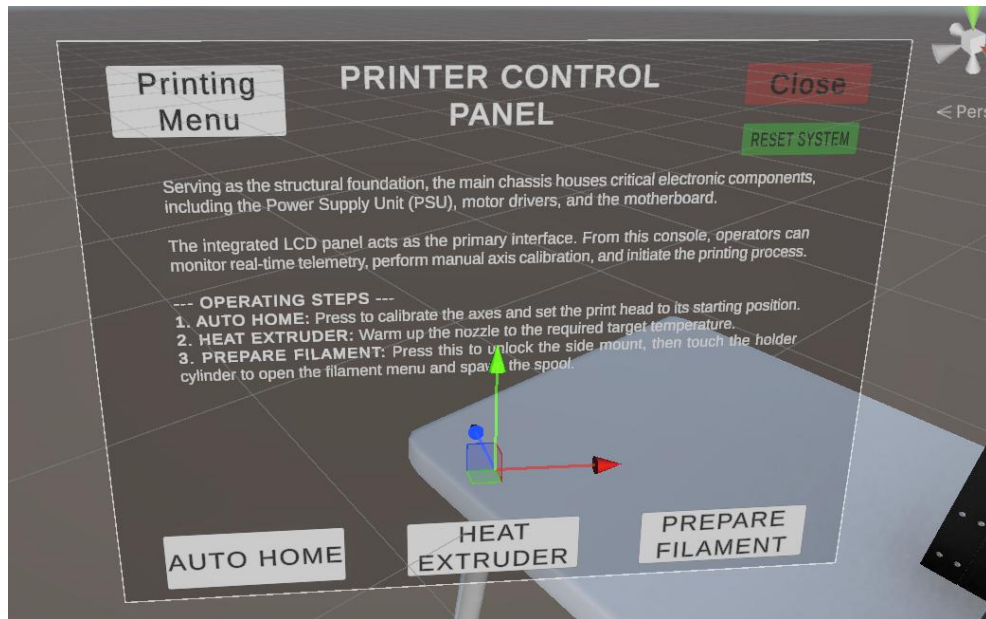


Fig. 4. World Space Canvas interface with the main control panel and print menu conditional on SD card detection

In terms of performance, the app runs consistently at 72 fps on the Meta Quest 3S, within the VR comfort threshold. Disabling snap grabbing components completely eliminated the jittering phenomenon identified in beta phases. Hand-tracking mechanics work both with controllers and in pure hand-tracking mode, without code changes.

The validation was carried out through sessions with users with no prior experience in operating FDM printers. Participants were able to go through the complete flow — from inserting the filament to lifting the piece — without verbal instructions or additional text, relying solely on visual cues and logical constraints of the interface.

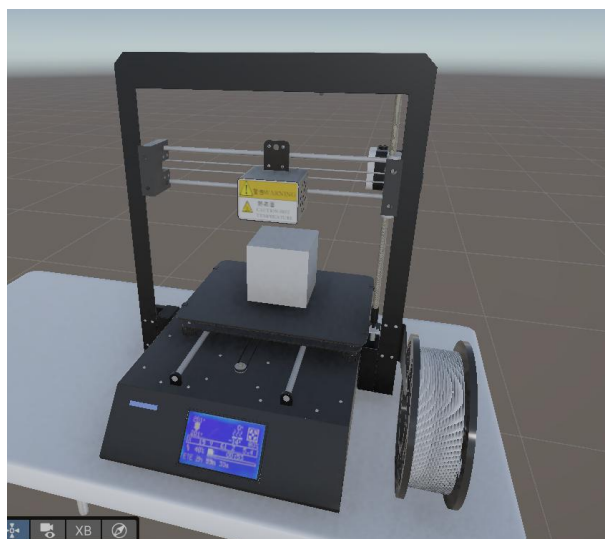


Fig. 5. The final result of the simulation – the part printed on the printer bed, interactive object (grabbable) at completion

5. Conclusions

The paper presents a functional VR simulator for the operation and calibration of FDM 3D printers, demonstrating that a complete procedural training flow can be implemented on accessible hardware (Meta Quest 3S standalone) with publicly available tools (Unity 6, Meta Interaction SDK). The main technical contributions are: (1) solving the post-snap jittering problem by programmatically disabling the grab components; (2) the conditional pagination logic of the Canvas interface, dependent on the physical state of the equipment; (3) simulation of multi-axis kinematics by C# Coroutines and linear interpolation; (4) Progressive clipping technique for visualizing printing layer by layer.

The future directions of development are aimed at expanding the realism and didactic value of the simulator. Priorities are: the introduction of simulated error scenarios (filament blockage, non-adhesion of the first layer, overheating), which require the user to identify the problem and apply the remediation procedure; expanding the library of printable parts; and the implementation of an automatic performance evaluation module, with score and detailed feedback at the end of the session. In the medium term, adapting the simulator to complementary technologies — SLA, SLS — would significantly expand its range of applicability in technical vocational training.

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Design of a Smart Manufacturing System Required for the Production of the Regenerated Catalyst Standpipe

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ABSTRACT: *This paper addresses the design of a smart manufacturing system based on Industry 4.0 principles for the Regenerated Catalyst Standpipe, a critical piece of equipment in the oil refining industry. The research aims to optimize the technological workflow by transitioning from conventional production methods—which are prone to human error and inefficiency due to the product's massive scale—to smart automation and robotic welding solutions. The ultimate objective is to increase productivity and execution quality through an integrated software and hardware system.*

KEYWORDS: *Smart manufacturing, Industry 4.0, Automation, Robotic welding, Regenerated Catalyst Standpipe.*

1. Introduction

1.1. Product Presentation: Regenerated Catalyst Standpipe

The analyzed product represents a vital component of the Fluid Catalytic Cracking (FCC) unit within a refinery. The functional role of this assembly is to ensure the circulation of the hot catalyst from the regeneration unit to the reactor. Given that this process is the foundation for transforming crude oil into high-quality gasoline, the standpipe must operate under severe conditions, withstanding temperatures that can reach 774°C and a highly abrasive and corrosive internal environment. From a structural perspective, this Fluid Catalytic Cracking equipment is a large-scale static assembly with a mass exceeding 18 tons, consisting of cylindrical shells, nozzles, and a thermal expansion compensation element. A 3D view of the product, generated using the Inventor CAD software solution, is illustrated in Figure 1.

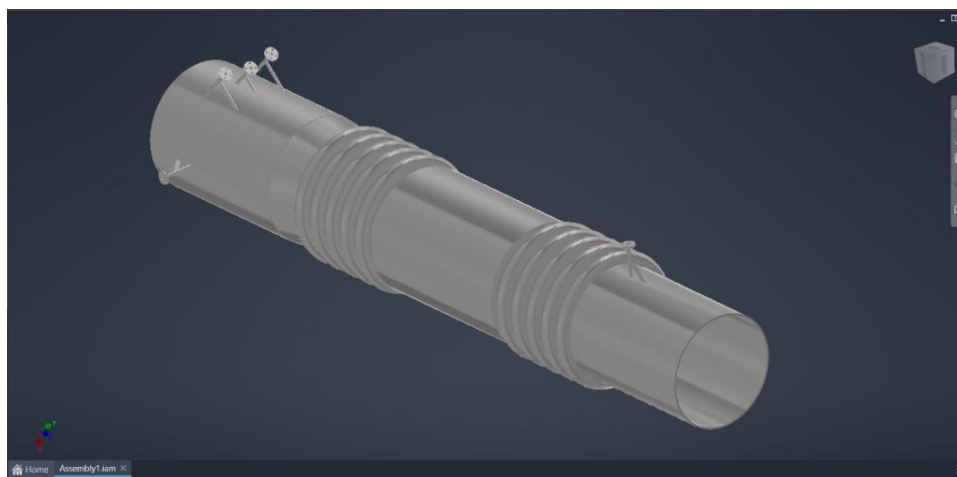


Fig. 1. 3D view of the Regenerated Catalyst Standpipe product

1.2. Purpose and objectives of the paper

The main purpose of this research paper is to identify and design a smart manufacturing system capable of modernizing the existing production process of this component. The specific objectives of the research include the optimization of the technological workflow, the integration of smart technologies, and the reduction of human resource involvement.

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1.3. Research methodology

To achieve the proposed objectives, the research methodology was structured into several logical stages:

- Technical analysis of the product: Studying the functional and geometric requirements to determine the needs of the manufacturing system.
- Study of theoretical foundations: Evaluating the concepts of Smart Manufacturing, Digital Twin, and IoT technologies applicable to the industrial environment.
- Comparative evaluation of technologies: Analyzing the differences between the conventional and the smart workflows.
- Design of the smart system: Defining the hardware and software structure of the system.

2. Product Analysis: Regenerated Catalyst Standpipe

2.1. Product role and functionality

The analyzed product plays a critical role in refining processes, serving as the primary means of transport that ensures the continuous flow of the hot catalyst from the regenerator to the base of the reactor. The functionality of the assembly is complex, ensuring the transport of the fluid under pressure and the absorption of major thermal expansions through the bellows-type expansion joint.

2.2. Fields of application

The standpipe is a large-scale static equipment, specially designed for use in severe industrial environments, being an indispensable component in the oil refining industry, specifically within Fluid Catalytic Cracking units.

2.3. Technical and functional requirements

Due to its operating regime, the assembly must guarantee perfect tightness and mechanical stability under heavy loads. An essential technical requirement is the geometric precision of the execution, considering that the part connects to the rest of the installation at a strict 35° angle; any deviation could compromise the final on-site assembly.

2.4. Materials used and properties

To withstand extreme temperatures and mechanical stresses, high-strength materials were selected:

- SA 516 Gr. 70 steel – used for the cylindrical shells, being an optimally alloyed carbon steel for pressure vessels and high-temperature service.
- ASTM A106 Gr. B steel – used for the nozzles, being a carbon steel pipe intended for high-temperature and high-pressure applications.

2.5. Constructive and geometric analysis

The assembly is defined by high geometric complexity and large dimensions, with a total length of over 7 meters and variable diameters of 990 and 1100 mm. From a constructive point of view, it consists of 16 mm thick cylindrical shells, a conical reducer, a nozzle system for fluid aeration, flanges, and an expansion joint.

2.6. Working conditions (temperature, pressure, corrosion)

The operating parameters are severe: the working pressure is 1.68 bar, and the operating fluid temperature is approximately 694°C, potentially reaching peaks of 774°C. The working medium (catalyst powder) is highly abrasive and hot-corrosive, which is why the design includes a 3 mm corrosion allowance to ensure the equipment's lifespan.

3. Theoretical Foundations of Smart Manufacturing

3.1. The Concept of Smart Manufacturing

Smart Manufacturing represents the evolution of production systems through the integration of advanced information and communication technologies into industrial processes. Unlike classical manufacturing, this concept relies on the systems' ability to self-optimize and

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adapt in real-time to changes in the production workflow.

3.2. Key Technologies (IoT, Big Data, AI)

The implementation of a smart system requires the use of specific technological pillars:

- Internet of Things (IoT): Represents the network of physical objects equipped with sensors and software, capable of collecting and exchanging data in real-time.
- Big Data: The processing of the large volume of data generated during the assembly's manufacturing process to identify efficiency patterns and prevent bottlenecks.
- Artificial Intelligence (AI): Provides manufacturing systems with learning and reasoning capabilities. AI algorithms are used to optimize working parameters, reducing human intervention in manufacturing processes.

3.3. Digital Twin and Process Simulation

The Digital Twin concept entails the virtual, dynamic, and faithful representation of a physical product, process, or system. Unlike a simple 3D model, the Digital Twin is constantly fed with data from the physical world, allowing synchronization between the two environments. Process simulation in this virtual environment allows for the testing and validation of different manufacturing scenarios without material risks or costs.

3.4. Automation of Industrial Processes

Modern automation involves the use of mechatronic structures and industrial robots to execute tasks with a high degree of repeatability and precision. In smart systems, automation is closely linked to information processing capacity, transitioning from the simple execution of a movement to its adaptation based on commands received from sensors.

3.5. Integration of CAD/CAM/CAE Systems

The efficiency of smart manufacturing is conditioned by the continuity of the digital data flow through the integration of IT systems:

- CAD (Computer-Aided Design): Used for computer-aided design and defining the product's geometry.
- CAM (Computer-Aided Manufacturing): Enables the computer-aided programming of execution equipment, transforming the geometric model into technological instructions.
- CAE (Computer-Aided Engineering): Facilitates the analysis and simulation of the product's engineering behavior (mechanical stresses, thermal stresses, etc.).

4. Conventional Manufacturing Technology of the Product

The conventional technological process for manufacturing the product relies on a sequence of cutting, plastic deformation, and welding assembly operations, where the operator plays the main role.

4.1. Cutting and preparation of semi-finished products

In the classical technological workflow, obtaining the components starts from raw semi-finished materials (plates and pipes). The operations are presented in the following table.

Tabel 1. Cutting and preparation operations of semi-finished products

No.	Process	Equipment used	Description
1.	Thermal cutting	Plasma cutting machine	The operator marks the contour on the plate with templates, followed by the actual cutting by guiding the source along the drawn lines.
2.	Mechanical cutting	Mechanical band saw	The operator measures and marks the dimensions on the pipes, followed by cutting to the corresponding lengths.

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- | | | | |
|----|------------------|---------|--|
| 3. | Edge preparation | Grinder | Processing the roughness and chamfers by manual grinding to prepare the part to be assembled by welding. |
|----|------------------|---------|--|

4.2. Cold plastic deformation (rolling)

Obtaining the cylindrical geometry of the shells is achieved through the cold rolling process on a 4-roll hydraulically driven plate rolling machine. This stage involves:

- Executing successive forward and backward passes to achieve the desired diameter without overheating the material.
- Constant verification of the curvature by the operator using templates.
- Finalizing the process by pre-bending the plate ends to ensure a uniform curvature and a proper joint for the longitudinal welding.

4.3. Welding processes

The information regarding the welding processes is presented in the following table:

			Tabel 2. Characteristics of the welding processes Equipment and parameters
No.	Assembled components	Welding process	
1.	Shells (butt joints)	SMAW (Shielded Metal Arc Welding)	Basic coated electrodes are used. The welder moves the electrode holder, applying oscillatory movements.
2.	Flanges on nozzles	TIG (Tungsten Inert Gas) + SMAW	The root pass is executed by TIG welding using a tungsten electrode and manual filler rod addition.
3.	Nozzles on shells (fillet joints)	SMAW	The process allows optimal maneuverability in difficult positions for welding at 90° and 45° angles.

5. Design of the smart manufacturing system

5.1. Defining the requirements of the manufacturing system

The transition to smart technologies represents the adaptation of the production process to Industry 4.0 standards, with the main goal of eliminating human error and downtime. The fundamental requirements of the system include the complete digitalization of the workflow and the integration of components into a digital infrastructure that allows communication between the designed model (CAD) and the execution machines (CNC/robots). The system must ensure a precision in the range of tenths of a millimeter and allow real-time monitoring of all working parameters.

5.2. Structure of the smart system (hardware + software)

The hardware structure of the system consists of state-of-the-art numerically controlled equipment. For processing semi-finished products, the system includes CNC plasma cutting machines for plate cutting, 3D laser cutting systems with an oscillating head, and CNC plate rolling machines. For the assembly phase, the hardware architecture uses robotic cells equipped with 6-axis articulated industrial robots. The software component integrates Nesting programs to automatically arrange parts on the plate and reduce waste, CAM software for generating numerical codes, and simulation platforms for the offline programming of robotic movements.

5.3. Integration of sensors and IoT systems

Smart equipment is endowed with advanced sensors that allow the automatic adjustment of processes. Plasma cutting machines use sensors to continuously measure the arc voltage, automatically adjusting the torch height relative to the metal sheet. During the welding process, the robotic cells integrate laser seam tracking sensors. These scan the surface in real-time, allowing the software to correct the welding head's trajectory in fractions of a second if geometric deviations from the rolling process occur.

5.4. Monitoring and control of the production process

Process control is achieved through digital touch interfaces and CNC systems that take over the task of intermediate verifications. For example, in the shell forming operation, the machine uses software that automatically calculates the kinematics of the rolls and the material's springback based on the inputted data (e.g., yield strength), eliminating repeated checks with a template. In the assembly phase, the industrial robot maintains a constant torch angle and travel speed. This constant monitoring allows the automatic execution of welding passes without the direct intervention of the welder.

5.5. Implementation of the Digital Twin concept

The Digital Twin concept is used to optimize production by creating a virtual replica of the physical processes. In the technological preparation phase, the engineer 3D simulates the robot's path around the standpipe using the programming software, thus validating the trajectories and avoiding collisions prior to the actual execution. Also, the plastic deformation equipment features virtual assistants and material databases to simulate the sheet's behavior. This digital thread ensures that the work programs are fully verified before the machines are physically started, greatly reducing the risk of errors in series production.

5.6. Analytical performance evaluation

To technically demonstrate the superiority of the proposed smart system over the conventional one, an analytical evaluation of the linear energy (heat input) introduced into the base material during the welding process is necessary. Linear energy represents the amount of heat introduced per unit length of the welded seam, being the parameter that directly influences residual stresses and thermal deformations.

The general calculation formula is:

$$E_l = \frac{\eta \times U_a \times I_s}{v_s} \quad (1)$$

Case 1: Conventional technological workflow (SMAW manual welding)

For joining the 16 mm thick plate shells, the conventional workflow involves the use of manual welding with a 4 mm diameter electrode. According to the welding regime analysis, the working parameters established for the human operator are: current intensity $I_s = 130$ A, arc voltage $U_a = 25$ V, welding speed $v_s = 1,93$ mm/s and a thermal efficiency $\eta = 0,8$. The introduced linear energy is determined by substituting the parameters into the basic formula:

$$E_{lclasic} = \frac{0.8 \times 25 \times 130}{1.93} = 1347 \frac{J}{mm} = 13.47 \frac{kJ}{cm} \quad (2)$$

Case 2: Smart technological workflow (MAG robotic welding)

In the proposed modern system, the robotic cell uses the MAG process, having as filler material a continuous solid wire with a diameter of 1.2 mm. Due to the precision and the laser seam tracking, the robot can maintain a much more productive regime: current intensity $I_s = 250$ A, arc voltage $U_a = 27$ V and welding speed $v_s = 7,5$ mm/s. Maintaining the same efficiency $\eta = 0,8$, the resulting linear energy is:

$$E_{lsmart} = \frac{0.8 \times 27 \times 250}{7.5} = 720 \frac{J}{mm} = 7.2 \text{ kJ/cm} \quad (3)$$

The comparative analysis of the two sets of results confirms the justification for the investment in automation. By transitioning to robotic welding, the processing speed increased from 1.93 mm/s to 7.5 mm/s, while the linear energy decreased from 13.47 kJ/cm to only 7.2 kJ/cm. This reduction in heat absorbed by the carbon steel material massively diminishes the thermal deformations of the elements.

6. Conclusions

The transition from conventional to smart methods eliminates the downtime and human errors associated with manual welding. The use of numerically controlled systems and robotic cells ensures high precision in manufacturing processes, guaranteeing the structural integrity of the product.

The analytical comparison demonstrated major advantages of the smart system:

- High productivity: Robotization allows for a welding speed approximately four times higher than that of conventional methods.
- Deformation control: Introducing a reduced amount of heat by decreasing the linear energy significantly diminishes the thermal stresses and deformations of the large-scale product.
- Resource savings: The high precision of smart systems allows for a reduction in the welding joint volume, leading to savings in filler material and energy.

Process automation also reduces personnel exposure to the risk factors associated with manual welding, ensuring a safer working environment. At the same time, the integration of real-time tracking sensors guarantees a consistent quality of the finished product, in compliance with the strict requirements of the oil refining industry.

The present paper has highlighted the benefits of digitalizing the production workflow through the implementation of the Digital Twin concept and offline programming. As a future research direction, the integration of artificial intelligence for the predictive monitoring of operating parameters and the automated diagnosis of welding defects can be explored.

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8. Nomenclature

The following symbols are used in this paper:

I_s = welding current intensity [A];

U_a = arc voltage [V];

v_s = welding speed [mm/s];

E_l = linear energy [kJ/cm];

η = thermal efficiency of welding.

THE DEVELOPMENT OF A MODULAR ROBOTIC ARM WITH INDUSTRIAL APPLICATIONS

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ABSTRACT: This paper tackles the development of a modular robotic arm with industrial applications. The design was realized using Autodesk Fusion, with modular design and additive manufacturing as design factors. The structural components were designed for FFF (Fused Filament Fabrication) manufacturing, utilizing polymers and geometric optimization which assure easy assembly. The system is driven by multiple servomotors and a stepper motor, being controlled by a Raspberry Pi RP2040 [1] microcontroller. The results obtained demonstrate the possibility of an accessible robotic arm, that's easy to fabricate and maintain, showing the potential of additive manufacturing in the domain of industrial robotics.

KEYWORDS: robotic arm, additive fabrication, robotic module, Raspberry Pi RP2040.

1. Introduction

Industrial robotics represents a foundational pillar of modern automation, contributing significantly to increasing productivity and reduction of human error in manufacturing. Even so, commercial robotic arms are often inaccessible from a financial point of view for small manufacturers, teaching labs, or enthusiasts. With this context, this paper proposes the development of a modular robotic arm, designed entirely for additive manufacturing, which combines functional performance together with low costs and ease of maintenance. The approach chosen is one that is based on utilizing the 3D FFF technology, of standard actuators and of a robust software architecture, with the aim of showing that open-source solutions can be viable alternatives in industrial and educational settings.

The increasing adoption of additive manufacturing technologies has significantly expanded the possibilities for rapid prototyping and functional robotic systems development. By combining modular mechanical architectures with accessible electronic platforms, researchers and engineers can create adaptable robotic solutions tailored to specific industrial requirements. Such systems offer reduced development costs, shorter implementation times and improved flexibility, making them suitable for educational environments, research laboratories and small-scale manufacturing applications.

2. Arm design

The mechanical design of the robotic arm was carried out using Autodesk Fusion, utilizing hybrid modelling techniques specific to the program's working environment, which allows for both solid modelling, as well as interactive management of assemblies, assuring an optimized geometry from a functional standpoint as well as an aesthetic standpoint (see figure 1). The architecture of the arm was designed around modularity, allowing the interchangeability of the toolhead depending on the intended application (gripper, extruder, sensor etc.).

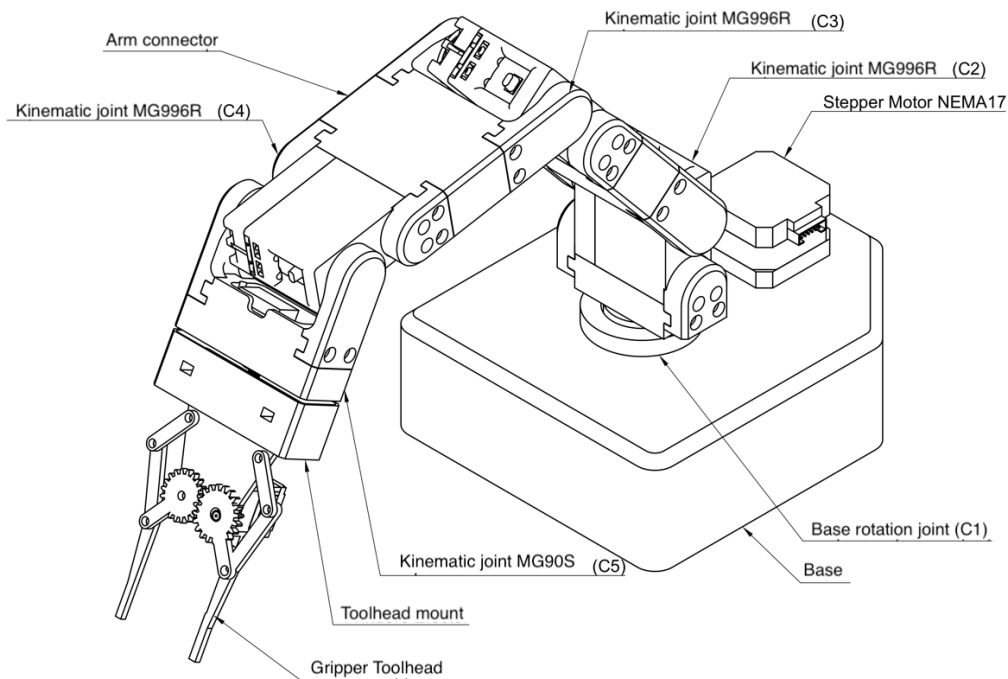


Fig. 1 Overview

The kinematic system is composed of five axes of movement, driven by a heterogeneous set of motors: three MG996R [2] servomotors for the main joints (see figure 2), a micro-servomotor MG90S [3] for the rotation of the toolhead and a stepper motor NEMA 17 [4] for the base rotation. This choice assures an optimal ratio between torque, precision and low cost of acquisition.

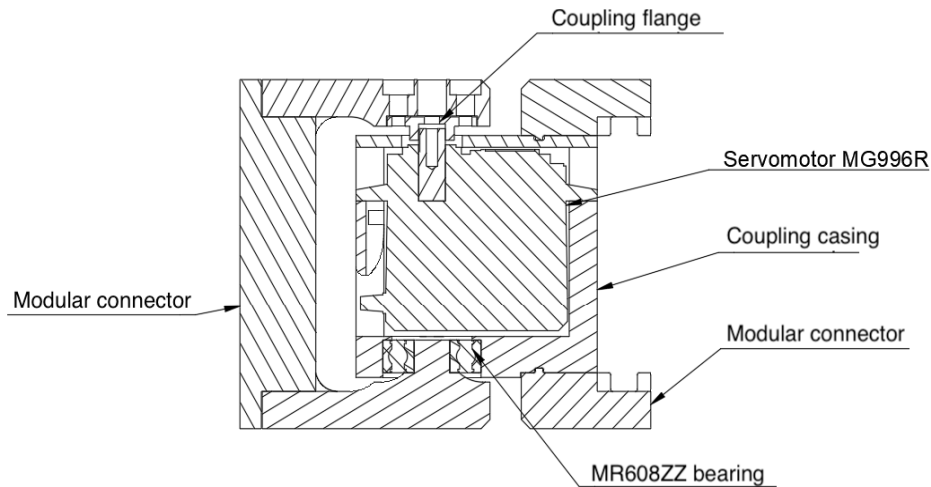


Fig. 2. MG996R kinematic joint section

All structural components have been designed exclusively for additive manufacturing. The bores and shafts include geometric compensations which allow assembly of bearings through press-fit mounting without further processing. In the main joints driven by MG996R servomotors, 608ZZ [5] ball bearings have been used, and in the base of the arm 608ZZ ball bearings have been used alongside a 51106 [6] thrust bearings. Assembly has been done utilizing M3 and M2 socket head cap screws (SHCS), assuring structural strength and a clean aesthetic.

3. Construction of the robotic arm

Manufacturing the components has been realized through 3D FFF printing on two performant 3D printers: Voron 0.2 and Creality K1. Before the manufacturing process, both printers were verified and calibrated to eliminate the perpendicularity deviations of the X and Y axes, which guarantees dimensional precision of the cylindrical features.

For printing, PETG and PETG-CF (PETG-carbon fiber composite) polymers were used due to high mechanical resistance and dimensional stability. The G-CODE programs for the 3D printers were created in the OrcaSlicer slicer. Advanced techniques were used such as bridge counterbore holes and exposed infill with multi-line infill, solutions which allow a significant reduction of the component masses without compromising rigidity. The infill process was chosen according to the stress level of each component: for the modular connectors made from PETG-CF this is between 7% and 15%. Multi-line infill allows the execution of a thicker infill compared to the standard variant, which handles mechanical loads more efficiently. For the modular connectors, a TPMS-D (Triply periodic Minimal Surface -- Diamond) [7] infill was chosen, a structure with an optimal distribution of internal stresses (see figures 3,4,5). For the other components, a 40% rectilinear infill with 3 perimeters was chosen.

THE DEVELOPMENT OF A MODULAR ROBOTIC ARM WITH INDUSTRIAL APPLICATIONS

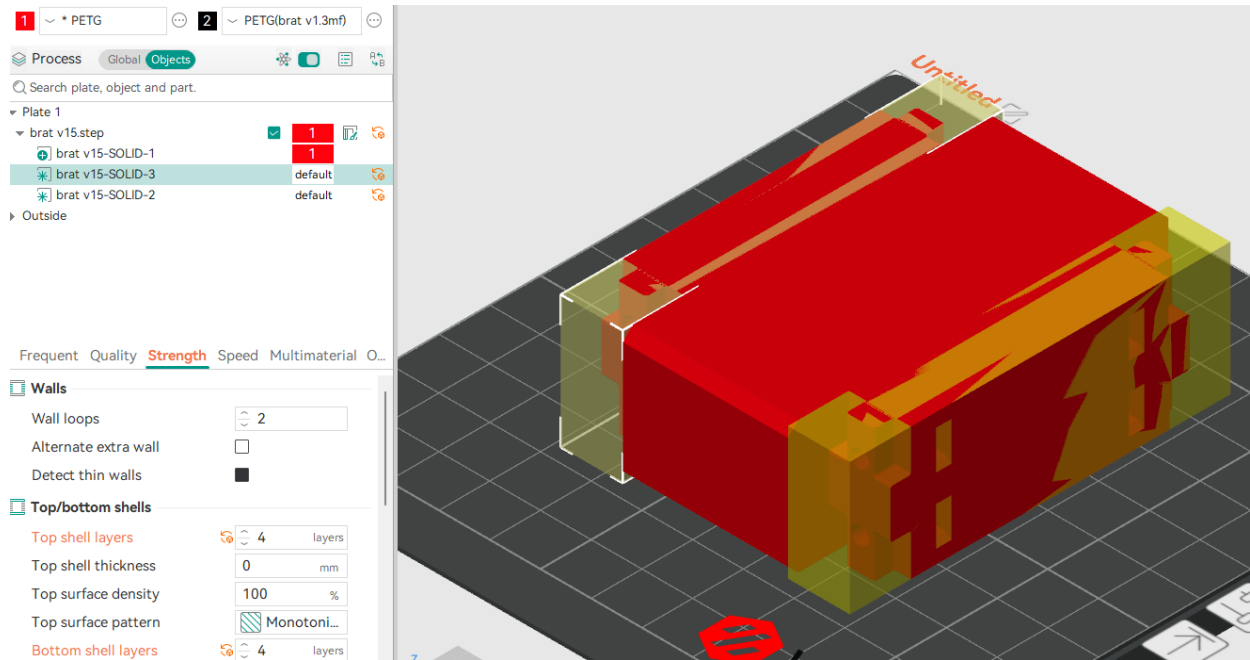


Fig. 3. Preparing the 3D model in OrcaSlicer

Because the part contains sections where it's necessary to have covered infill, modifiers are to be used, represented as transparent yellow boxes, with options top/bottom shell layers = 4.

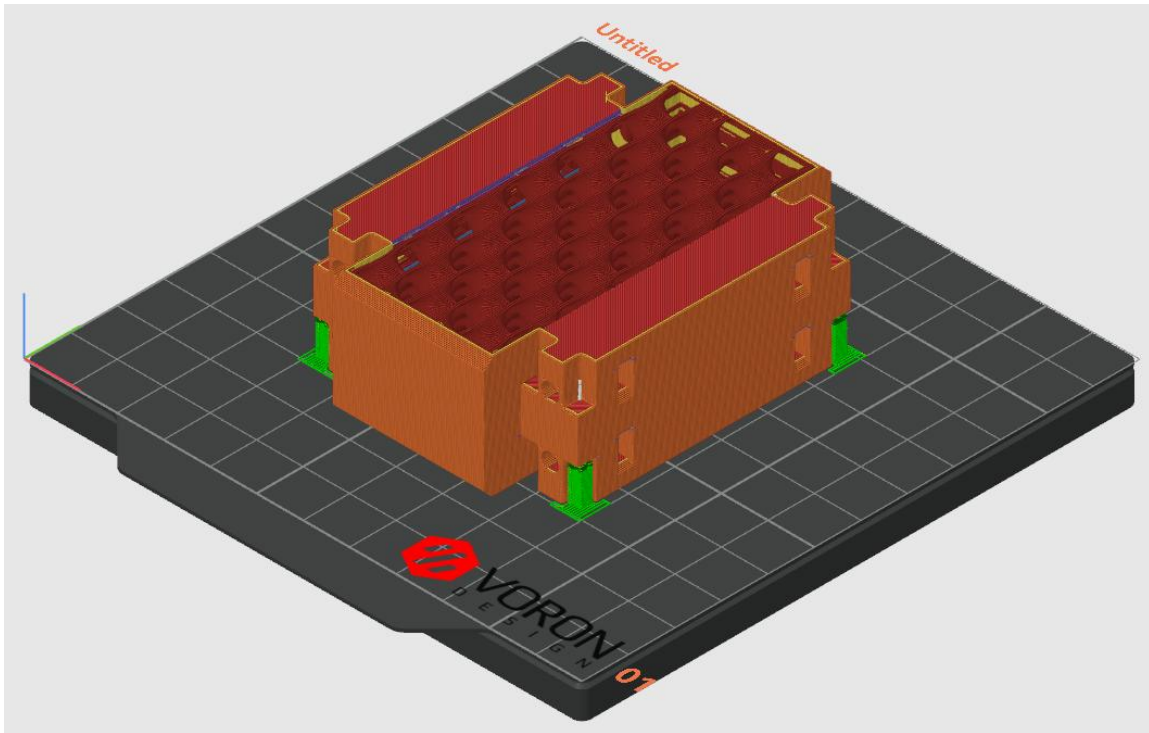


Fig 4. Voron 0.2 G-CODE file preview

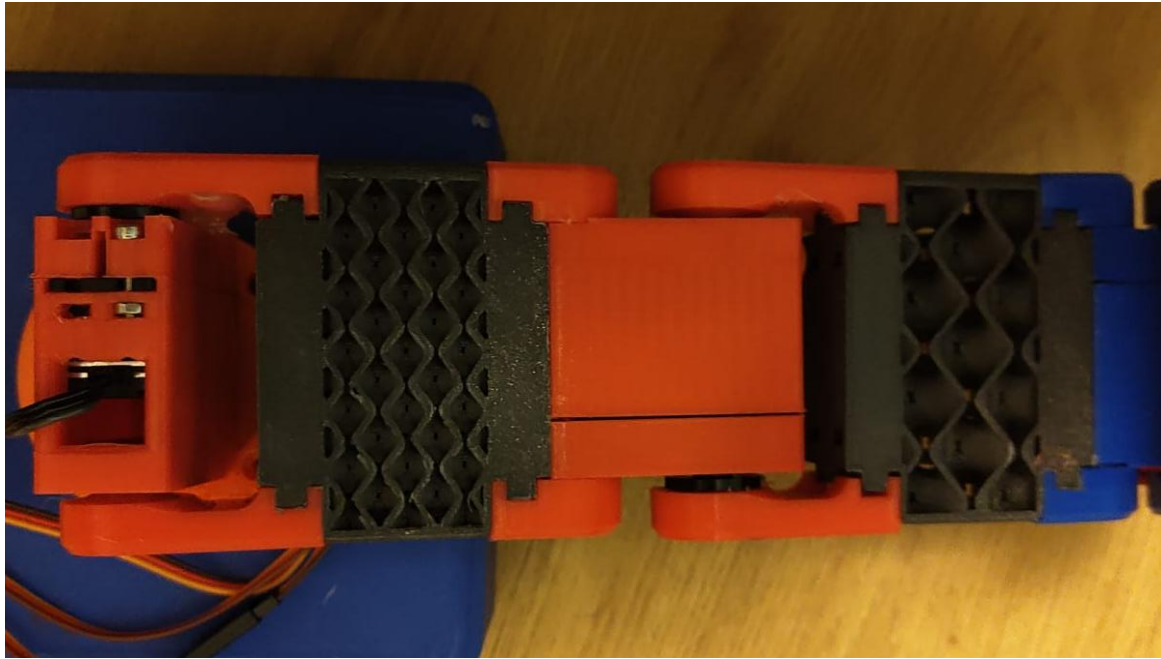


Fig. 5. Showcasing of the modular connectors in the assembly

The modular connector concept also contributes to improved maintainability and scalability of the robotic platform. Individual modules can be replaced or upgraded without requiring modifications to the entire assembly, reducing downtime and simplifying maintenance procedures. This approach supports future extensions of the robotic arm, allowing the integration of additional sensors, end-effectors or structural elements according to the requirements of specific industrial applications.

Assembly of the arm proved to be fast and intuitive, due to the accessibility-oriented design approach: all contact surfaces and fixture points have been positioned to allow easy manipulation of components and easy fastening of screws with standard tools (see figure 6).

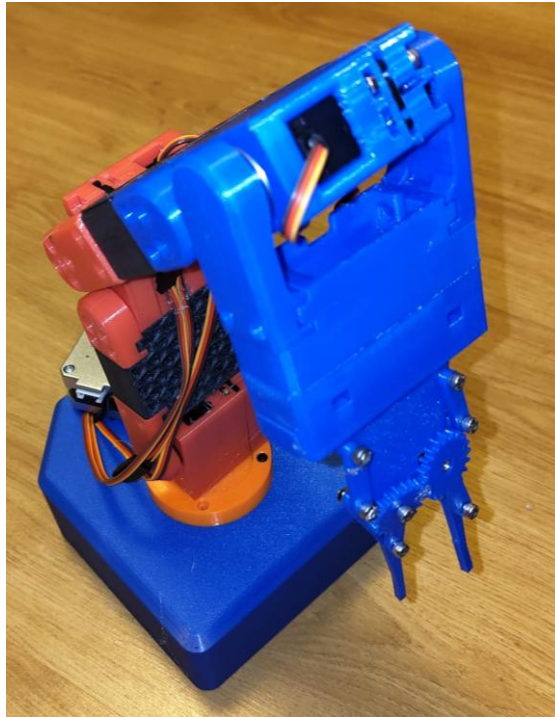


Fig. 6. Prototype of the robotic arm assembled with a gripper effector.

From a power electronics point of view, the system is powered through a USB-C Power Delivery (PD) [8] board, which automatically negotiates the voltage of 20 V from a 65 W charger. The voltage of 20 V directly powers the NEMA17 stepper motor's driver (TMC2209) [9], while the buck converters lower the voltage to 6 V for servomotors and 5 V for the microcontroller and host. The TMC2209 driver allows the silent control of the stepper motor. The homing of the base axis is performed using an Omron D2F endstop (see figure 7).

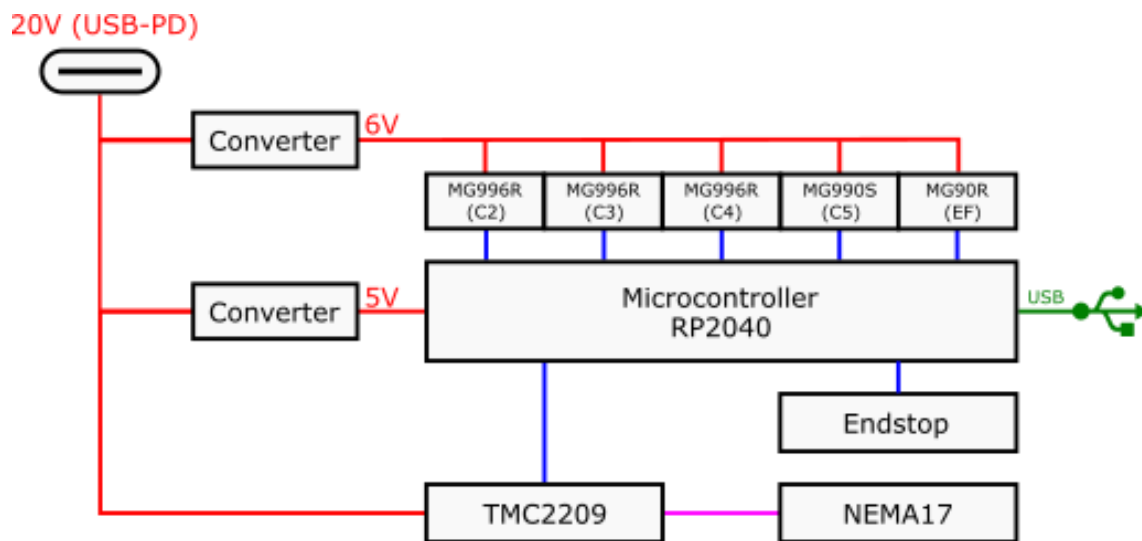


Fig. 7. Electronic diagram

4. Programming the arm

The control system of the robotic arm is based on the RP2040 microcontroller, chosen for its performance at accessible prices. The software architecture is modular and is composed of two main systems: the firmware, which runs on the microcontroller, and the host which runs on any computer with Linux, Windows or macOS.

The firmware's duty is direct control over motors and sensor data acquisition. To ensure maximum stability, especially for the emergency stop functionality (E-STOP), the firmware implementation avoids dynamic memory allocations and possible memory corruption. Communication between the firmware and host is done through a custom binary protocol, designed for reliability: this includes a timestamp for synchronized command execution, and a CRC (Cyclic Redundancy Check) field for data integrity (see figure 8).

Length 2 bytes	Sequence number 1 byte	Flags 1 byte	Payload N bytes	CRC 1/2 bytes
Length (little-endian) of the packet [seq+flags+payload].	Wrap-around packet ID for packet retransmission and duplicate detection	Bitfield. 1 = Response 0 = NAK.	Max 512 bytes. Postcard data request/response	CRC-8/16 [seq + flags + payload]

Fig. 8. Communication packet structure

The software project was implemented in the Rust programming language because it has a wide array of libraries and many characteristics which allow the compiler to find issues at compile time (not during operation). The project is modularized into multiple components: arm-command (the control language interpreter), armd (host application), config (firmware configuration), firmware-common and firmware-rp2040 (hardware platform-specific code), protocol (common communication library) and xtask (build support).

System configuration is done through TOML files, allowing for the definition of motors, joints, communication ports and other operational parameters.

Communication with the host is done through WebSockets, the client sends commands in the control language, and it receives back a response though status codes (ex. E0 = OK, E1 = Parse error).

The control language is inspired by the G-CODE standard, tailored for robotic arms. It allows the definition of positioning modes and joint commands though concise instructions, with support for repeating parameters (see figure 9).

```

1 | A1 M0 # Set absolute positioning mode, M1 is relative
2 | A5 J1 P90 # Move the first joint to absolute position 90
3 | A5 J2 P45 # Move the second joint to absolute position 45
4 | P 120 # Move the second joint to absolute position 120
5 | # A0 is also repeatable, but requires X, Y and Z
6 | A0 J1 X100 Y200 Z50 # In Cartesian mode, move the end effector to 100, 200,
7 | Y 250 # Repeat the same command but with Y=250, resulting in 100, 250, 50

```

Fig. 9. Command sequence with comments

5. Current state and possible improvements

A priority development direction focuses on improving the system precision by implementing feedback control loops. Experimental tests revealed that MG996R servomotors

present significant variations in quality and reliability, some demonstrating excessive mechanical play, which limits positioning repeatability in industrial applications.

In the medium term, the development of a high-quality robotics platform is wanted, with high manufacturing and documentation standards, with a similar philosophy of that found in open-source projects such as Voron 3D printers, having as an objective a viable and accessible alternative to robotic industrial arms.

Another direction of development focuses on creating an improved version which utilizes larger stepper motors, assuring stronger and more precise joints. This version will integrate both additive manufacturing elements and readily available prefabricated components, including sheet metal components and GT2 transmission belts, with the aim of reducing manufacturing time and increasing the rigidity of the assembly.

6. Conclusions

This project demonstrates the viability of creating a modular robotic arm through additive manufacturing methods, resulting in a functional platform, accessible pricewise and easy to maintain. Integration of computer aided design in Autodesk Fusion with FFF manufacturing allowed for reduced development time and a fast iteration of geometry. The advanced 3D printing techniques and composite materials used lead to a sufficiently rigid structure, but with a reduced mass, improving the arm's dynamics.

From a software point of view, the modular architecture implemented in Rust and the robust communication protocol offers a strong base for extending functionality, while hardware validation highlighted the need for a rigorous selection of actuators for industrial applications which require high precision.

This project demonstrated the feasibility of developing a modular robotic arm using a combination of additive manufacturing techniques, commercially available electronic components and open-source software solutions. The integration of computer-aided design, rapid prototyping and embedded control systems enabled the realization of a functional robotic platform with reduced manufacturing costs and development time.

Experimental evaluation confirmed that the proposed architecture provides sufficient structural rigidity for educational and light industrial applications while maintaining a high degree of modularity. The use of interchangeable modules allows future upgrades and customization according to specific operational requirements.

The project also highlighted several aspects that can be improved in future developments. Higher precision actuators, enhanced feedback systems and closed-loop control strategies could significantly increase positioning accuracy and repeatability. Additional optimization of the mechanical structure, including the use of reinforced materials and hybrid manufacturing techniques, would further improve stiffness and load-carrying capability.

Overall, the proposed robotic arm represents a cost-effective and scalable solution that demonstrates the potential of combining additive manufacturing and modular design principles for the development of modern robotic systems. The obtained results provide a solid foundation for future research focused on industrial automation, intelligent manufacturing and advanced robotic applications.

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DEGRADATION OF THE MECHANICAL PROPERTIES OF POLYCARBONATE EXPOSED TO UV-C RADIATION

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ABSTRACT: *This paper investigates the degradation of the mechanical properties of 3D-printed polycarbonate (PC) specimens exposed to UV-C radiation. The specimens were 3D printed using polycarbonate and subjected to accelerated UV-C aging inside a controlled exposure chamber for different exposure times. After the aging process, the samples were experimentally tested under tensile, compression, and three-point bending loading conditions according to the corresponding testing standards. The study evaluates the influence of UV-C radiation on the mechanical behavior, stiffness, and strength of the material after exposure to ultraviolet radiation. Experimental results provide insight into the durability and performance of 3D-printed polycarbonate components operating in UV radiation environments.*

KEYWORDS: *Polycarbonate, UV-C radiation, Aging, Mechanical properties, Degradation*

1. Introduction

Polycarbonate (PC) is a widely used engineering thermoplastic, valued for its high impact resistance and mechanical strength. A drawback of polycarbonate is its sensitivity to ultraviolet radiation, particularly in the UV-C range (100-280 nm), which represents a small portion of solar radiation at ground level. [1,2]

When exposed to UV-C radiation, polycarbonate undergoes structural changes at the molecular level that eventually affect its macroscopic behavior. Over time, this leads to increased brittleness and a reduction in tensile strength and elongation at break [1, 3, 4]. For 3D-printed PC-based parts, the response is more nuanced: after 24 hours of UV-C exposure at $\lambda = 254$ nm, the tensile strength of ABS-PC remained almost unchanged (≈ 39 MPa, control vs. exposed), while stiffness decreased by 5.2% and compressive strength by 6.5% [2]. In the case of black-pigmented PC, the carbon black filler provides a barrier against UV radiation that can slow surface degradation; however, it does not prevent the gradual deterioration of mechanical properties under prolonged exposure. [1]

For this study, samples were subjected to accelerated aging under controlled laboratory conditions, followed by various testing methods. The goal of this work is to measure how much the mechanical properties change depending on how long the samples were exposed, and to understand what causes these changes.

2. Current state of Research

Polycarbonate is already used in many applications where the material must resist impact, bending, or repeated handling. Because of this, it is not enough to know only its initial properties. Exposure to sunlight or artificial UV sources varies the material's properties in time and it is changing its behavior in tensile tests, noticed through lower elongation, different fracture response and sometimes changes in tensile strength. [1,5]

Several studies discuss the influence of UV on polycarbonate, but the results are not always identical, because the degradation depends on exposure time, radiation type and the specimen thickness and material formulation also need to be considered [1,2,4]. In the case of black polycarbonate, the situation is slightly different from transparent PC, because carbon black can block part of the UV radiation and may slow down the aging process. Still, this does not mean that the protection is assured, so the material must be tested experimentally instead of assuming that the color makes it stable. [6]

For this paper, the most researched part is the mechanical response after UV-C

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exposure, not only the general aging of the material. The specimens are tested in tension, compression and for three-point bending, so the main values followed are force, displacement, stress, strain, Young's modulus and elongation at break. ARAMIS [7] is useful here because it shows how the deformation is distributed on the specimen surface, not only the final value from the testing machine. In this way, the test can show if the specimen is deformed uniformly or if strain starts to concentrate in a certain area before fracture.

3. Materials and Methods

3.1 Specimen fabrication

All specimens were 3D printed using black polycarbonate filament (Raise3D Premium PC Black) on a Raise3D E2 FDM printer. The printing temperature was set to 260°C and the bed temperature was 105°C. Four types of specimens were produced, corresponding to the mechanical tests carried out in this study: dog-bone specimens for tensile testing (ASTM 638-1), prismatic and cylindrical specimens for compression testing (ASTM D695) and rectangular beams for three-point bending (ISO 178). The geometry of each specimen is shown in Figure 1. A total of 60 specimens were fabricated: 15 for each type. [8, 9, 10]

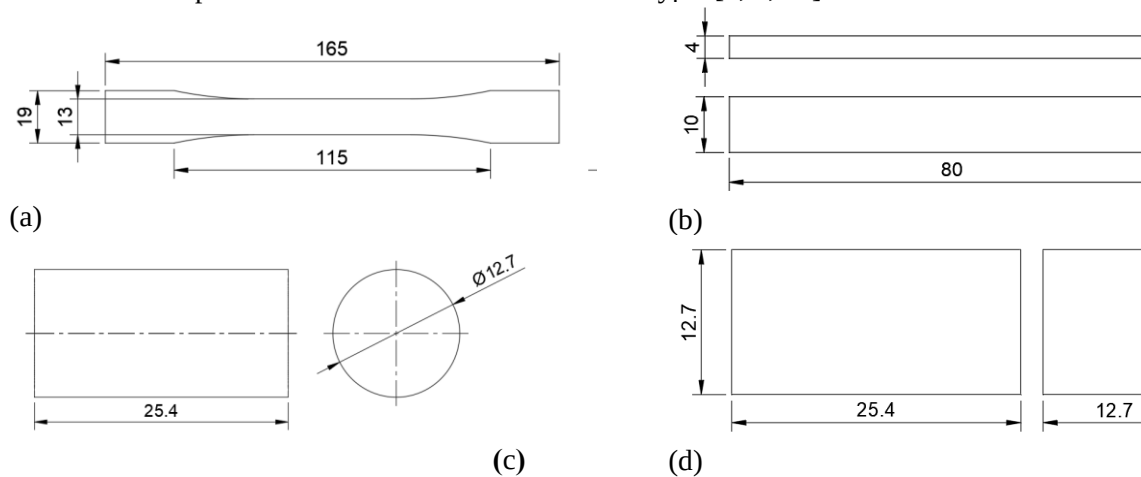


Figure 1. Geometry of the printed specimens: (a) tensile ASTM 638-1 (b) three-point bending ISO 178 (c) and (d) compression ASTM D695

3.2 UV-C exposure

Specimens were exposed to UV-C radiation in an Opsytec Dr. Gröbel BS-02 irradiation chamber (Figure 2), equipped with mirrored internal surfaces on both sides to ensure uniform radiation distribution. For this study, the UV-C lamp at $\lambda=280$ nm was used at 100% intensity. All specimens were positioned vertically inside the chamber; this differs from the approach used in [2], where specimens were placed flat on the chamber floor, limiting direct exposure to one face only. The 15 specimens from each type were divided into 5 groups of 3. The first group received no UV exposure, while the other 4 groups were exposed for cumulative durations of 2, 4, 8, and 24 hours with 3 specimens from each type removed at each interval.

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Figure 2. Specimens exposed to UV in the irradiation chamber

4. Results

The results of the tensile tests carried out according to ASTM D638-1 on the black polycarbonate specimens are summarized in Table 1, with the corresponding stress-strain curves shown in Figure 3. After UV-C exposure, the tensile strength $\sigma_{\max}$ remains practically unchanged (variation below 1.5 % compared to the 0 h reference), while the Young's modulus E decreases progressively with exposure time, reaching a reduction of approximately 5.7 % at 8 h, followed by a slight recovery at 24 h ($\Delta \approx -4.0$ %). The elongation at break ϵ_{break} increases at all exposure levels (+6 % ... +23 % compared to 0 h), and the dispersion of the results is higher for E and ϵ_{break} , which indicates a non-uniform surface degradation of the material. Overall, UV-C exposure up to 24 h produces a slight reduction in stiffness and an increase in ductility, without significant embrittlement of the black polycarbonate.

Table 1. Tensile properties of Black PC specimens vs. UV-C exposure (ASTM D638-1)

UV-C exposure (h)	$\sigma_{\max}$ Aver. (MPa)	$\sigma_{\max}$ St. dev.	$\Delta\sigma_{\max}$ vs 0 h [%]	E Aver. (MPa)	E St. dev.	ΔE vs 0 h [%]	ϵ_{break} Aver. (-)	ϵ_{break} St. dev.	$\Delta\epsilon_{\text{break}}$ vs 0 h [%]
0	44.33	0.87	—	2010	93	—	0.0544	0.0020	—
2	44.52	0.20	+0.41	1964	23	-2.30	0.0663	0.0036	+21.97
4	44.37	0.08	+0.08	1925	55	-4.23	0.0609	0.0078	+11.99
8	43.95	0.51	-0.86	1895	120	-5.73	0.0576	0.0049	+5.99
24	43.73	0.33	-1.36	1929	12	-4.01	0.0667	0.0106	+22.67

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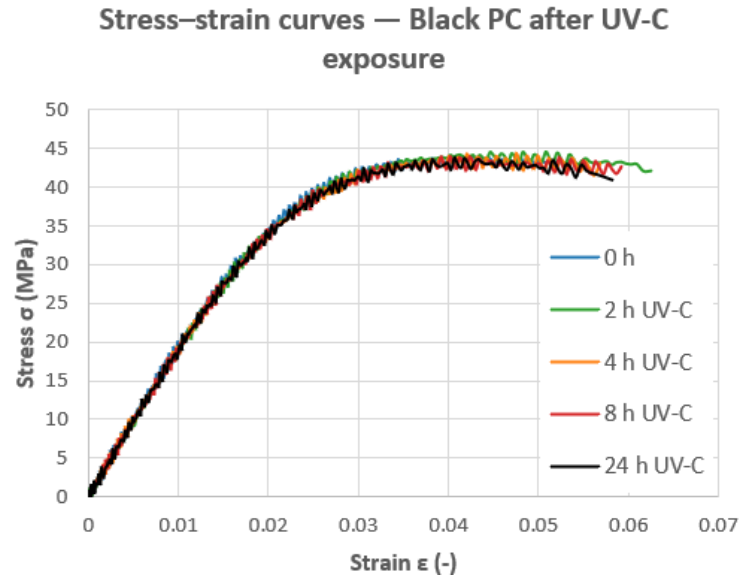


Figure 3. Representative stress-strain curves for each exposure time

The von Mises strain maps obtained with ARAMIS for the control specimen and the 24 h exposed specimen are shown in Figure 3. The control specimen (0 h) shows a sharp strain localization in a narrow zone just before fracture, while the 24 h specimen displays a more distributed deformation pattern with a higher peak strain (32.6% vs. 26.6%), consistent with the increased elongation at break recorded in Table 1.

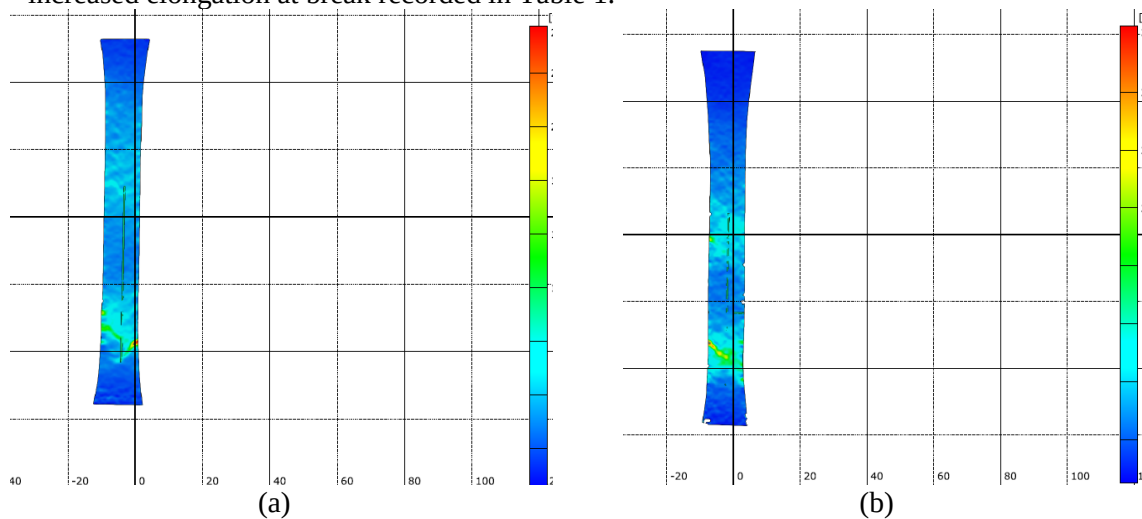


Figure 4. Von Mises strain maps: (a) no UV exposure, (b) 24h UV exposure

In the case of bending tests, results show a mild stiffness gain after intermediate UV exposure (Figure 5): average flexural modulus increases from 1600 MPa at 0h to 1746 MPa at 8h (9.1%), then falls to 1539 MPa at 24h (Table 2). Flexural strength is comparatively stable, ranging from 70.5 to 72.9 MPa and peaking around 8h; strain at maximum stress remains close to 6.83-6.97%. Overall, the 4-8h exposure range gives the best bending stiffness/strength balance, while 24h shows lower stiffness and the highest scatter.

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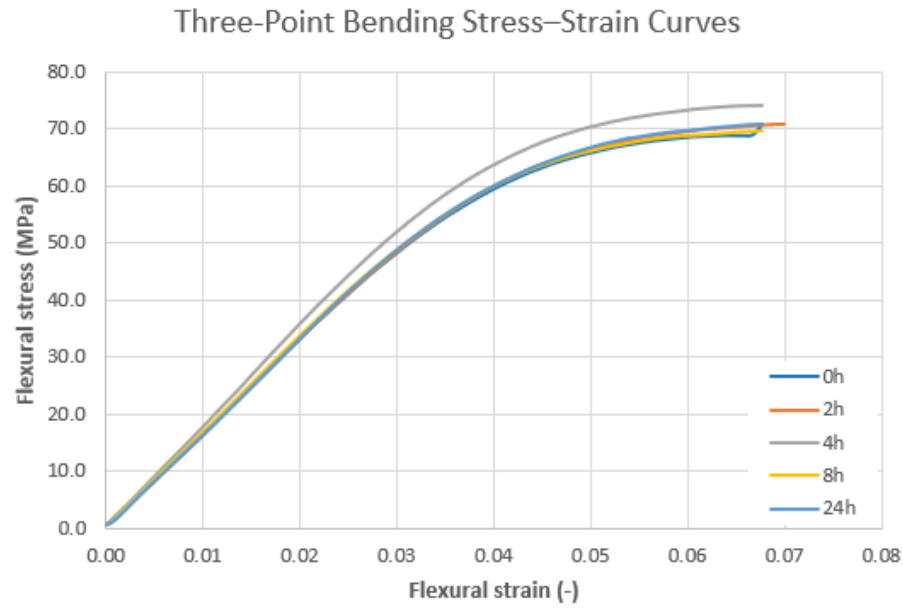


Figure 5. Representative stress-strain curves for each exposure time

Table 2. Flexural properties of Black PC specimens vs. UV-C exposure (ISO 178)

UV-C exposure (h)	$\sigma_{\max}$ Aver. (MPa)	$\sigma_{\max}$ St. dev.	$\Delta\sigma_{\max}$ vs 0 h [%]	E Aver. (MPa)	E St. dev.	ΔE vs 0 h [%]	Stiffness Aver. (N/mm)	Stiffness St. Dev.	Δ Stiffness vs 0 h [%]
0	70.5	1.1	—	1600	58	—	15.6	0.6	—
2	70.7	3.9	+0.3	1519	117	−5	14.8	1.1	−5.0%
4	72.9	2.4	+3.4	1716	46	+7.2	16.8	0.4	7.2%
8	72.9	2.3	+3.4	1746	86	+9.1	17	0.8	9.1%
24	71.9	1.2	+1.9	1539	167	−3.8	15	1.6	−3.8%

Compression tests used cylindrical specimens ($\varnothing 12.7 \times 25.4$ mm), which gave more uniform contact under the platens and lower scatter than the prismatic geometry. As shown in Table 3, UV-C exposure has almost no effect on the compressive response of the black polycarbonate. The compressive strength $\sigma_{\max}$ stays within about ± 4 % of the 0 h value (between -1.94 % and $+3.71$ %, averaging close to 55 MPa), and the Young's modulus E varies by less than ± 1.2 % across all exposure times (1054 – 1070 MPa). Up to 24 h of UV-C exposure, neither the compressive strength nor the stiffness changes significantly (Figure 6).

Table 3. Compressive properties of Black PC cylindrical specimens vs. UV-C exposure (ASTM D695)

UV-C exposure (h)	$\sigma_{\max}$ Aver. (MPa)	$\sigma_{\max}$ St. dev.	$\Delta\sigma_{\max}$ vs 0 h [%]	E Aver. (MPa)	E St. dev.	ΔE vs 0 h [%]
0	54.62	3.62	—	1057.5	2.2	—

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2	54.73	3.53	+0.20	1058.6	26.8	+0.10
4	53.56	2.13	-1.94	1054.0	8.8	-0.33
8	56.17	1.24	+2.83	1069.8	1.7	+1.16
24	56.65	0.86	+3.71	1059.2	27.0	+0.16

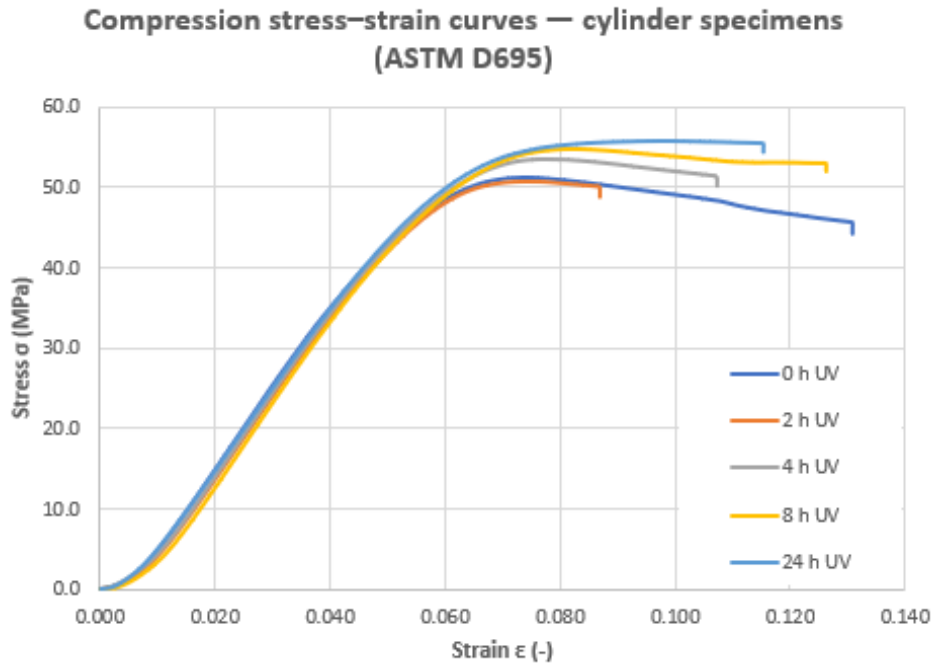


Figure 6. Representative stress-strain curves for each exposure time

5. Conclusions

Black polycarbonate proved considerably more resistant to short-term UV-C exposure than the transparent grades reported in the literature [1, 3, 5], confirming the protective role of the carbon black filler suggested in [1, 6]. Across all three loading modes, the material did not show the classical embrittlement pattern (loss of strength combined with a drop in elongation) typically associated with UV aging of polycarbonate. The dominant effect was a moderate softening of the surface layer that produced a slightly more ductile response for the tensile tests and a small increase in data scatter, while flexural and compressive properties remained essentially unchanged up to 24 h.

Visual inspection of the tested specimens (Figure 6) is consistent with the mechanical data: the tensile specimens exposed for longer durations show only a slight matte surface compared to the unaged reference, with ductile fracture surfaces and no brittle features typical of severely UV-degraded polycarbonate, while the bending and compression specimens show almost no visible cracking.

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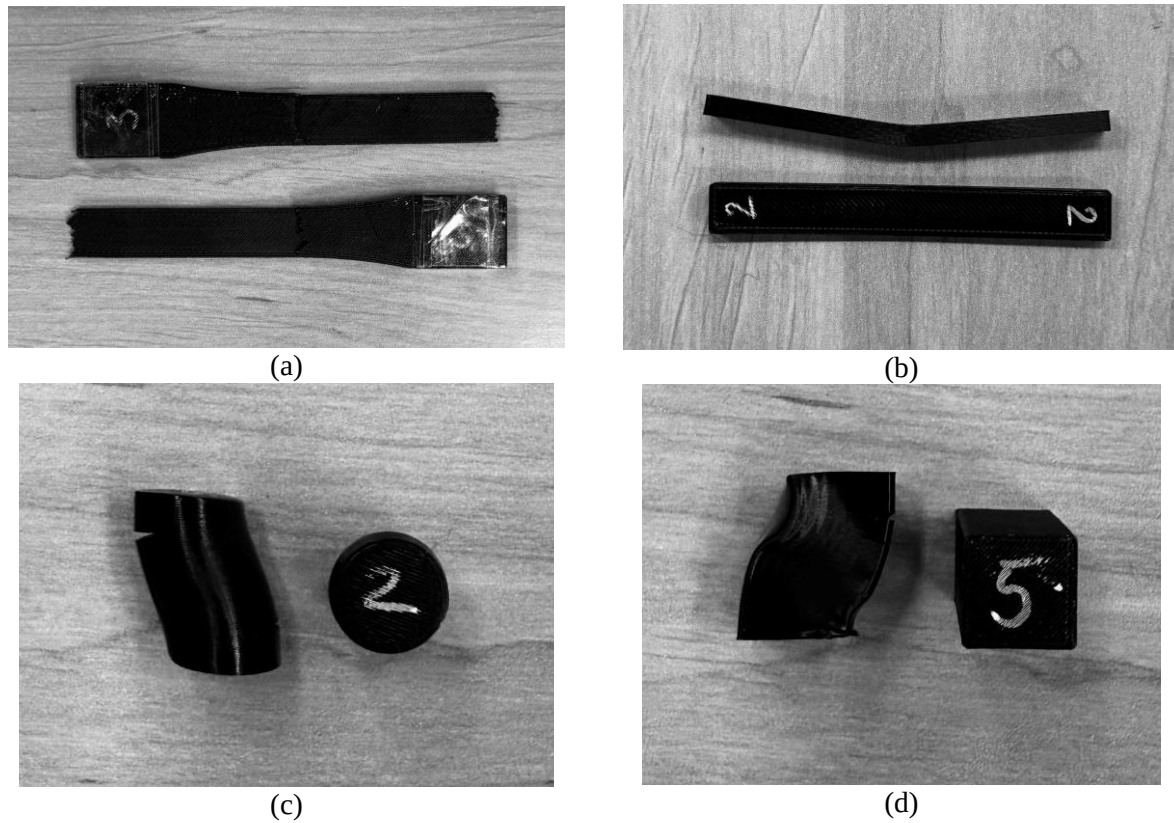


Figure 6. Specimens after testing: (a) tensile, (b) three-point bending, (c) and (d) compression

The study was motivated by the lack of consistent data on UV-C aging of 3D-printed black polycarbonate specifically, since previous works address transparent PC sheets [1, 3, 5] or ABS-PC blends with single-face flat exposure [2]. Placing FDM-printed specimens vertically inside a mirrored chamber and testing the same material across three loading modes allows the effect of UV-C to be isolated from the geometric and material variability of those earlier studies, and shows that for $\lambda \approx 280$ nm exposures up to 24 h the carbon black filler is sufficient to preserve the mechanical response of the material.

Repeating and extending the study is worthwhile: the 24 h window is too short to capture the long-term degradation reported for artificial weathering of polycarbonate [3, 4, 5], and several trends in the present data (decreasing flexural modulus, rising scatter at 24 h, slight recovery of E in tension at 24 h) suggest that the material is on the verge of a degradation regime that was not reached here. A follow-up campaign should extend the exposure times to at least 100–200 h with intermediate sampling points, and ideally combine UV-C with humidity or thermal cycling to better approximate service conditions. The experiments can be improved by enlarging the sample size beyond three specimens per group, rotating the specimens inside the chamber to homogenize the dose, measuring the irradiance at the specimen surface with a calibrated sensor instead of relying on the lamp setting, complementing the mechanical tests with surface characterization, and testing transparent and black PC in parallel under identical conditions to quantify the actual protective effect of the carbon black filler.

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PLASTIC MATERIAL INFLUENCE OVER THE GEOMETRICAL CHARACTERISTICS OF THE FLEX SPLINE FROM THE HARMONIC DRIVE GEARBOX

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ABSTRACT: This paper presents the conception, design and physical realization of a strain wave generator model. The 3D model was created in the CATIA v5 program, the element targeted by the strength tests was imported into the ANSYS Mechanical program where it was verified under static loads. The physical model was created by additive manufacturing with plastic materials. The results show the possibility of using such a reducer in a concrete application.

CUVINTE CHEIE: proiectare 3D, manufacturare aditivă, analiza elementului finit, reductor armonic, CATIA v5, ANSYS Mechanical.

1. Introducere:

Lucrarea de față își propune să studieze solicitarea statică maximă pe care elementul deformabil din cadrul unui reductor armonic o poate suporta, plecând de la caracteristicile termoplasticului poliuretan (TPU) și geometria specifică a acestuia. Pentru studierea rezistenței, se va utiliza analiza elementului finit prin intermediul soft-ului ANSYS Mechanical, iar pentru demonstrarea fezabilității unui reductor armonic realizat din material plastic, s-a realizat o machetă printată 3D după modelul realizat în CATIA v5 (fig. 1).

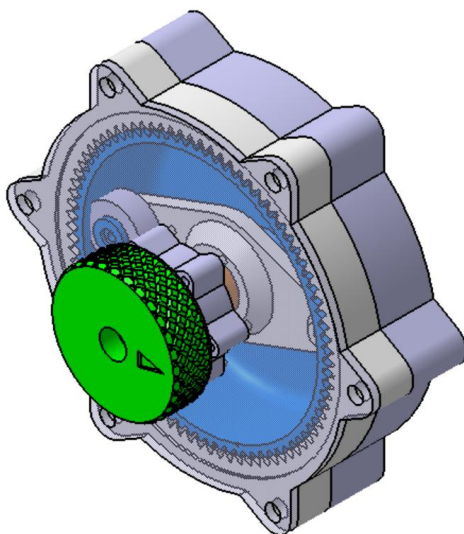


Fig. 1 Modelul 3D al reductorului armonic în soft-ul CATIA v5

2. Stadiul actual

Până în prezent am reușit să concepem un reductor armonic modular, ale cărui componente pot fi înlocuite cu ușurință pentru facilitarea testării fizice a mai multor geometrii sau materiale. Alături de ansamblul fizic, am realizat și teste utilizând analiza elementului finit în ANSYS Mechanical din care a reieșit solicitarea statică maximă la care poate fi supus elementul deformabil din componența reductorului.

3. Reductorul armonic

Reductorul armonic este un mecanism compact dedicat reducerii turației și amplificării cuplului într-un spațiu redus în comparație cu transmisiile tradiționale. Alături de reductorul cicloidal și planetar este preferat pentru utilizarea în domeniul roboticii industriale datorită celor două caracteristici definitorii ale acestuia: dimensiunile reduse în comparație cu raportul de transmitere ridicat, unde se aseamănă cu celelalte două reductoare și jocului funcțional inexistent, specific acestui tip de reductor.

În componența sa, reductorul armonic cuprinde patru elemente specifice: coroana dințată, elementul deformabil, rulmenții deformatori și deformatorul.

Primul brevet de invenție pentru acest tip de reductor a fost înregistrat în anul 1959, de către americanul C. W. Musser. Acesta descrie în detaliu părțile componente ale reductorului, principiul de funcționare, geometria danturii coroanei și elementului deformabil, dar prezintă și relații de rezistență și dimensionare pentru dantură și elementul deformabil.

Principiul de funcționare al reductorului armonic se bazează pe deformarea continuă prin care trece elementul deformabil, elastic prin natura sa. Deformatorul împinge pereții elementului elastic în două puncte diametral opuse pe circumferința interiorului acestuia, astfel deformându-l într-o configurație eliptică. Datorită elasticității, dantura elementului deformabil va intra în contact mereu cu coroana dințată, astfel eliminându-se jocul funcțional caracteristic angrenajelor tradiționale precum angrenajul cilindric, conic sau melcat.

În practică, materialul din care este confecționat elementul deformabil este un oțel special tratat, obținut prin mijloace costisitoare, dedicat deformării continue, astfel, conform producătorului Harmonic Drive, sub solicitări potrivite, elementul elastic nu va ceda la oboseală niciodată. În ultimul timp, datorită prețurilor tot mai accesibile ale imprimantelor 3D, au apărut diverse proiecte ce imită arhitecturi de roboți industriali, în special braț articulat, ale căror axe comandate numeric conțin reductoare cicloidale și armonice, mai puțin planetare.

Pentru proiectarea reductorului armonic am folosit relațiile de calcul prezentate în brevetul de invenție din 1957. Spre deosebire de dinții angrenajelor cilindrice sau conice, a căror formă este dată de curba evolventă la diametrul de bază, dinții elementului deformabil și coroanei dințate au formă triunghiulară, cu flancurile drepte.



Fig. 2 Profilul evolvent al unui dinte dintr-un angrenaj cilindric

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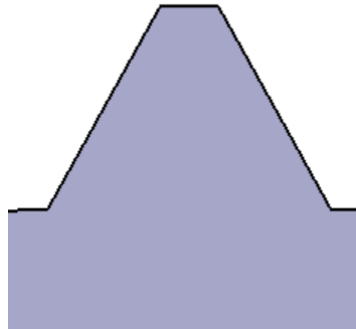


Fig. 3 Profilul drept al unui dinte al elementului deformabil

În urma proiectării danturii și elaborarea unei carcase care să cuprindă toate elementele reductorului am obținut un ansamblu funcțional. Ansamblul a fost conceput modular pentru ca în viitor să putem modifica cu ușurință unele componente pentru efectuarea unor teste sau probării unor dimensiuni de coroană sau element flexibil.

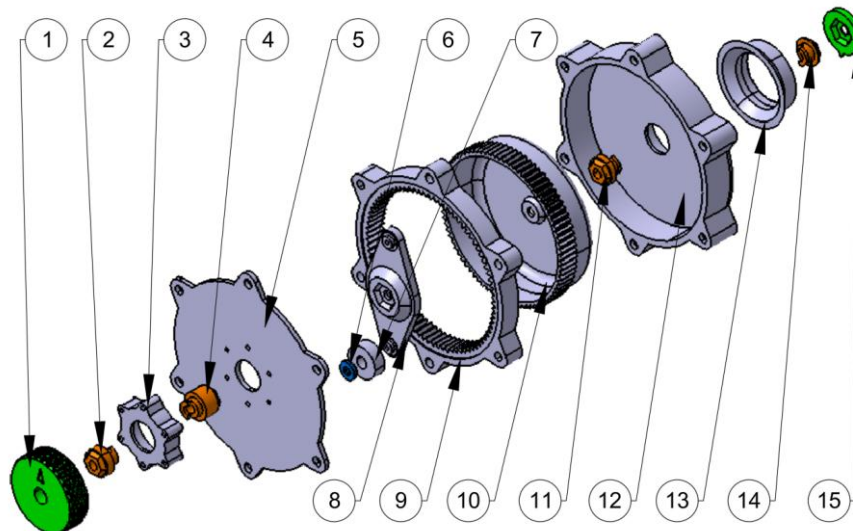


Fig. 4 Vedere explodată a reductorului armonhic proiectat

Modelul de reductor armonhic include următoarele componente:

1. Mâner pentru rotirea arborelui;
2. Arbore de intrare cuplat la mâner;
3. Carcasa rulmentului pentru lăgăruirea arborelui de intrare;
4. Arborele de intrare cuplat cu deformatorul;
5. Capac transparent;
6. Șaibă;
7. Rulment deformator;
8. Deformatorul;
9. Coroana dințată;
10. Elementul deformabil;
11. Arborele de ieșire cuplat cu elementul deformabil;
12. Carcasă;
13. Cadran;
14. Arbore de ieșire cuplat la acul indicator;
15. Ac indicator.

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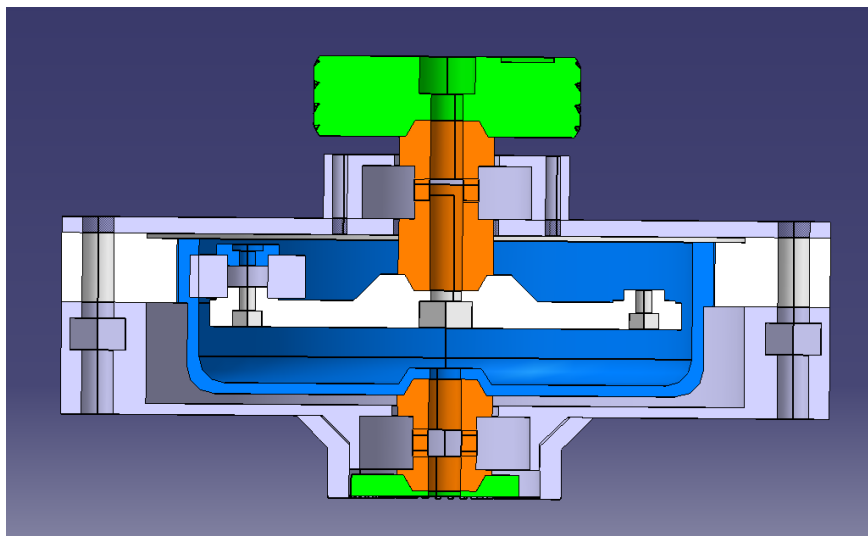


Fig. 5 Vedere în secțiune a reductorului armonic proiectat

4. Proiectarea în CATIA v5

Reductorul a fost realizat în format parametric pornindu-se de la numărul de dinți și de la modul, fiind calculați toți ceilalți parametri dimensionali ai transmisiei.

	A	B	C
1	m	1,50	
2	zc	100,00	
3	zf	98,00	
4	n	2,00	
5	P	0,67	
6	p	4712,39	
7	t	2,06	
8	d	3,00	
9	D	22,00	
10	Perete	2,00	
11	rootDelta	1,84	
12	tipDelta	1,22 d*0,40625	
13	Dr_c	150,00	
14	Dr_f	150,00	
15	Dr_eff	147,00 m*zc-d	
16	D_relax	145,75 m*zc-1,416*d	
17	radius_c	75,00 m*zc/2	
18	radius_f	72,88 (m*zc-1,416*d)/2	
19	D_root_f	143,31 m*zc-2,2285*d	
20	ElementFlexibil_d_int	69,66 (m*zc-2,2285*d)/2-Perete	
21			
22	D_deformator-r	60,78125 (m*zc-0,8125*d)/2-Perete-D/2	
23	D_deformator_tot	71,78125	

Fig. 6 Parametri folosiți în proiectarea reductorului

Mai întâi au fost realizate formulele în excel, apoi transpuse în CATIA v5. Parametrizarea ne-a permis să testăm cu ușurință mai multe combinații valorice și a grăbi procesul de prototipare.

Toate piesele din componența reductorului armonic au fost scoase la imprimantă 3D, cu excepția rulmenților, șuruburilor și piulițelor. Materialul folosit la imprimare a fost acid polilactic (PLA) datorită rigidității sale ridicate, iar pentru elementul flexibil a fost folosit TPU

Pentru realizarea prototipului didactic de reductor armonic s-a optat pentru metoda de fabricație aditiva de tip FDM (Fused Deposition Modeling). Principalul atu al acestei tehnologii este pretul redus al imprimantelor 3D cu filament și costurile reduse de exploatare, iar rezultatele procesului sunt adecvate scopului urmărit în lucrarea de față.

5. Realizarea modelului fizic al reductorului

5.1. Limitări ale procesului FDM întampinate în procesul de proiectare

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Pentru a se atinge rezultate optime în funcționarea reductorului s-au luat în considerare particularitățile procesului de printare 3D încă din etapa de proiectare CAD. Principalele limitări impuse de proces ce au trebuit depășite au fost: dimensiunea duzei, anticiparea orientării optime a pieselor pentru a minimiza materialul de susținere și ranforsarea elementelor defavorizate de anizotropia construcției pe straturi imperfect omogene.

- Dimensiunea duzei:
Imprimanta folosită este dotată cu o duză standard cu un orificiu de 0,4 mm ce oferă un raport bun între debitul maxim de material (indirect viteza de printare) și rezoluția maximă a detaliilor executate de mașină. Un aspect critic în reușita proiectului este buna realizare a danturii elementelor angrenate, cât mai aproape de modelul teoretic realizat în proiectarea CAD. În acest scop am efectuat încercări de verificare a capacității imprimantei de a reproduce angrenaje cilindrice cu module mici și am constatat o performanță mulțumitoare pentru valori începând cu modulul angrenajului $m=0,8$ [mm]. Pentru prototipul în discuție, având în vedere scopul său de model didactic, am optat pentru un modul de 1.5 [mm], astfel crescând gabaritul pentru o mai bună ilustrare a principiului de funcționare.
- Orientarea pieselor:
O particularitate a procesului este utilizarea de material-suport pentru a susține depunerea materialului pe suprafețele suspendate ale modelului. Acest proces este necesar pentru a se realiza anumite geometrii în produsul final, dar utilizarea suportului se dorește a fi evitată pentru a se scurta timpul de fabricație și materialul folosit. Prin utilizarea unor artificii de design se poate evita aproape complet necesitatea folosirii structurilor suplimentare de susținere.
- Ranforsarea elementelor defavorizate de anizotropia procesului.

Prin natura procesului de depunerea a filamentului extrudat la cald și răcirii sale rapide nu se obține o omogenizare perfectă între planurile straturilor ce alcătuiesc produsul final și prin urmare, corpurile astfel obținute sunt anizotrope. În timpul procesului de proiectare s-au luat în calcul atât orientarea optimă a fiecărei piese pe patul de printare (astfel încât forțele ce vor acționa asupra acestora să le solicite în direcția cu proprietăți mecanice superioare), dar și să satisfacă cerința materialului de susținere. În cazul arborilor reductorului s-a întâlnit o situație ce la prima vedere forțează un compromis: Orientarea verticală este optimă pentru printare, dar produsul finit este slab la solicitări radiale și momente de torsiune, iar orientarea orizontală preia mai bine forțele, dar este suboptimă pentru execuție. Pentru a rezolva dilema, s-a optat pentru printarea verticală a arborelui și ranforsarea acestuia cu un ansamblu șurub-piuliță ce comprimă piesa și îi îmbunătățește astfel proprietățile structurale.

5.2. Cum a îmbunătățit procesul de printare 3D produsul final

Procesul de fabricație aditivă a dus la realizarea, în anumite privințe, a unui produs final superior față de metodele clasice de manufactură. Prin înțelegerea procesului și optimizarea modelului s-au obținut următoarele atuuri ale machetei: Integrarea ușoară a elementelor de asamblare în corpul reductorului:

Modelul CAD prevede o serie de cavități hexagonale în corpul carcasei, imposibil de a fi fabricate prin oricare alt proces tradițional. La momentul potrivit, în construcția stratificată a piesei, imprimanta este programată să se oprească pentru a permite operatorului să insereze câte o piuliță în fiecare dintre cavitățile respective și să repornească ulterior procesul. Astfel, produsul final prezintă corpuri de

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asamblare nedemontabile, iar filetele metalice conferă longevitate modelului didactic.

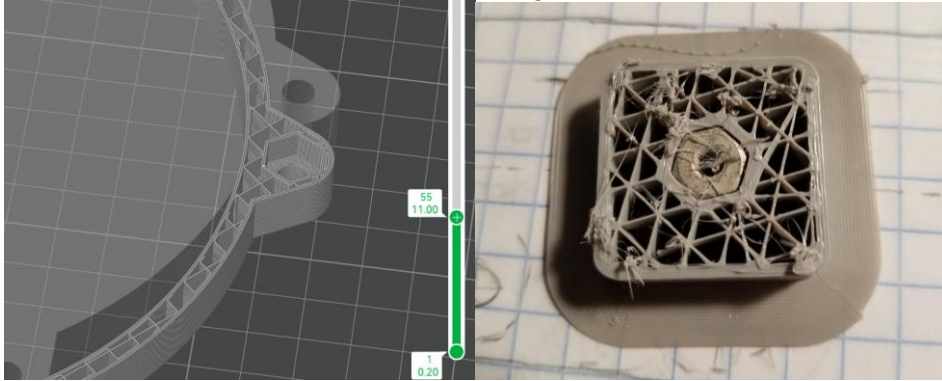


Fig. 7 Exemplificarea procesului de incastrare a piulitelor

- Piese pot avea în interior o structură optimizată pentru a crește rigiditatea specifică, îmbunătăți distribuția masei, micșora timpul de fabricație și a minimiza materialul folosit:

Procesele de fabricație aditivă facilitează realizarea structurilor celulare (structuri cu miez ușurat / de tip sandwich), soluție tehnică preferată de industria aerospațială datorită rigidității specifice ridicate (raportul dintre rigiditate și greutate), dar limitată în practică de costul ridicat de realizare prin metode de producție clasice. Avantajele acestor structuri reies din formula momentului de inerție (Steiner):

$$I = \sum_{i=1}^n A_i d_i^2$$

Se poate observa că aportul pe care îl are o porțiune de arie din secțiune în calculul momentului de inerție este direct proporțională cu pătratul distanței față de planul median. Prin urmare, structurile celulare distribuie materialul de în mod optim pentru a se obține o rigiditate specifică maximă. Fabricația aditivă favorizează realizarea de structuri cu miez ușurat nu numai din considerente structurale, dar și datorită costurilor reduse prin economisirea de material și al timpului mai scurt de fabricație.



Fig. 8 Vedere explodată a unei structuri de tip sandwich

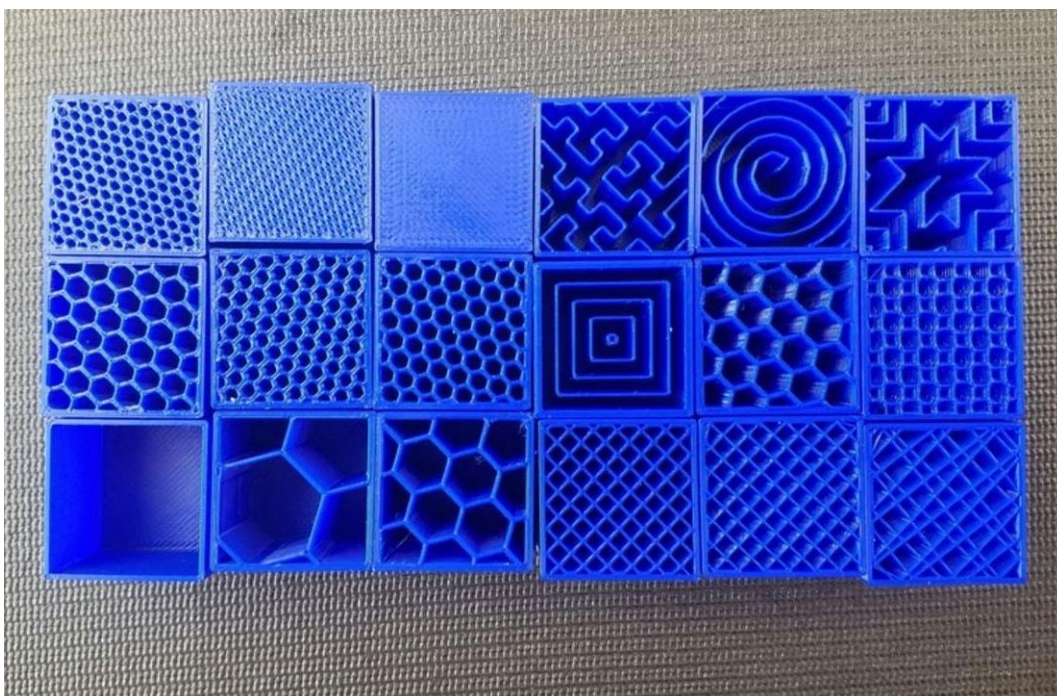


Fig. 9 Exemple de structuri celulare utilizate în fabricatia aditiva

- Facilitarea realizării unor soluții mecanice deosebite, nepractice de executat prin metode tradiționale de manufacturare:

Printarea 3D oferă un nivel deosebit de libertate proiectantului în realizarea de soluții constructive deosebite, nepractice în mod tradițional din cauza costurilor prohibitive. De exemplu, în designul reductorului s-a optat pentru transmiterea cuplului prin formă, folosindu-se o porțiune hexagonală pe capătul de arbore și negativul acesteia pe piesa condusă. Mai mult, pentru a asigura centrarea elementelor, cele 2 suprafețe prezintă teșituri ce acționează ca în cazul suprafețelor conice în cazul corpurilor de revoluție pentru realizarea alinierii pieselor. Un beneficiu suplimentar este asigurat de distribuția forțelor în momentul încărcării structurii: când ansamblul transmite o forță de rotație, cele 2 corpuri îmbinate tind să se deplaseze axial datorită suprafețelor de contact ce acționează ca niște planuri înclinate, direcție raforsată de șurubul care trece prin interiorul arborelui și strânge tot ansamblul

împreună.

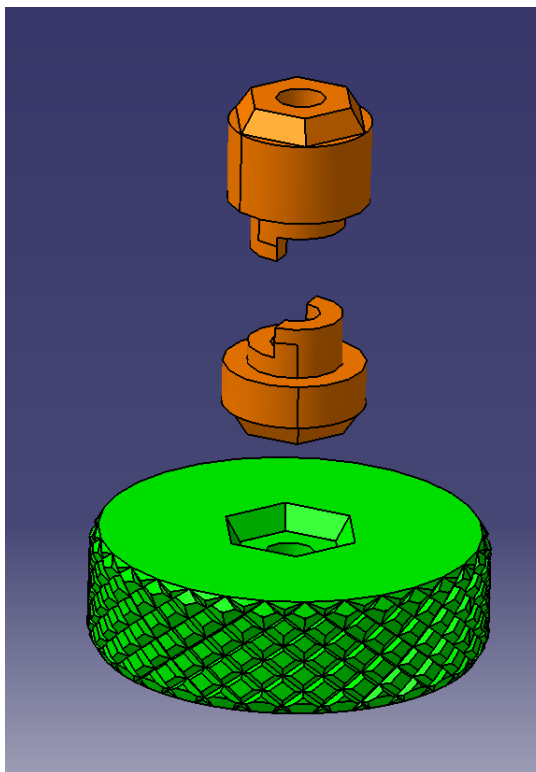


Fig. 10 Vedere explodată a soluției de transmitere a cuplului în reductor

Încă o geometrie deosebită este folosită pentru îmbinarea celor 2 jumătăți de arbore și fixarea rulmentului. Pentru această provocare nu s-a optat pentru metoda clasică de presare a rulmentului prin ajustaj cu strângere pe arbore, ci s-a ales o metodă inedită, posibilă datorită procesului de fabricație aditivă. Prin împărțirea arborelui în 2 părți s-a obținut avantajul că reducerea de diametru necesară îmbinării cu rulmentul să nu afecteze dimensiunile capetelor de arbore, iar pentru a evita orice deplasare între părțile ansamblului s-a realizat un montaj prin formă prin secționarea simetrică a celor 2 porțiuni de arbore și extinderea lor pentru a se suprapune.

5.3. Realizarea prototipului didactic:

Piesele printate 3D au fost realizate pe o imprimantă 3D Bambu Lab A1, model recunoscut pentru rezoluția sporită de printare. Pentru realizarea instrucțiunilor program mașină de tip G code s-a optat pentru Bambu Studio. Fig. 6 Exemplificarea procesului de încastrare a piulițelor.

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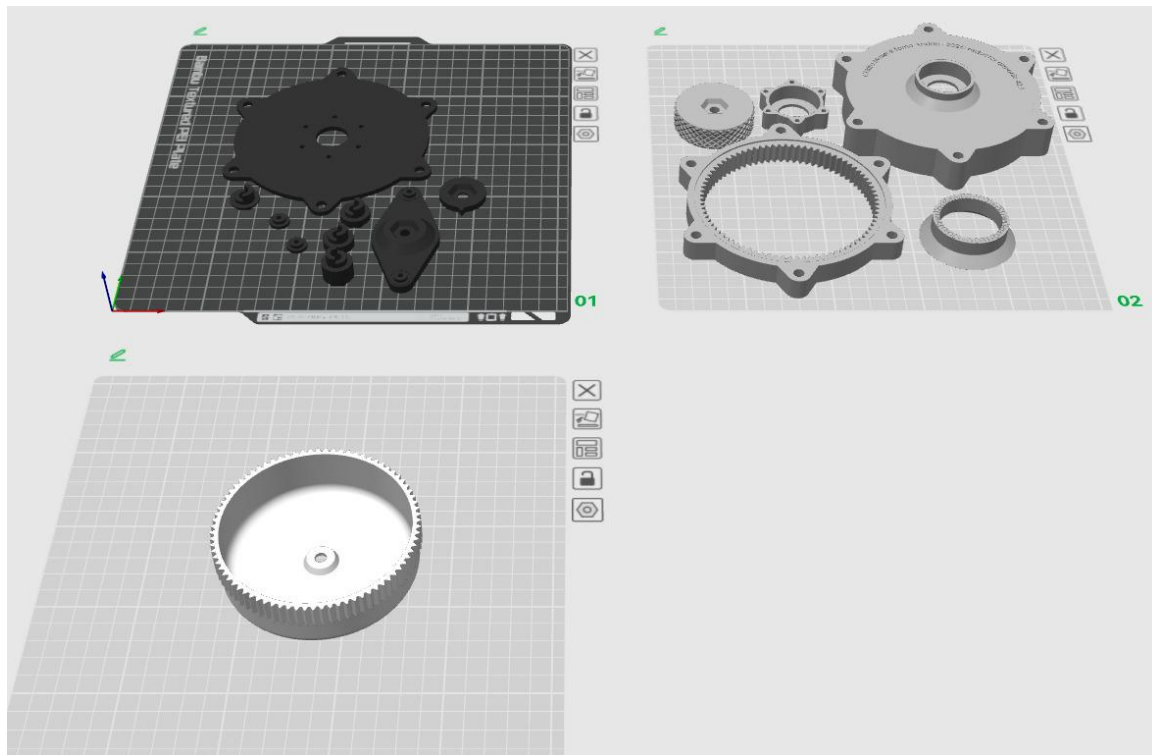


Fig. 11 Impartirea pieselor in functie de material in vederea printarii

5.4. Realizarea capacului transparent:

Pentru realizarea capacului transparent s-a optat pentru o placă de 3mm din acril (polimer polimetilmetacrilat) datorită ușurinței în prelucrare și a proprietăților mecanice mulmumitoare.

Pentru cele 2 machete didactice au fost folosite abordări cât se poate de diferite pentru prelucrarea plăcii de plexiglas. Pentru primul capac s-au folosit metode tradiționale de realizare a prototipurilor, folosindu-se scule manuale. În figura 11 stânga, se observă metoda de debitare a conturului exterior. Folosindu-se un traforaj electric, tăierea a fost realizată urmărindu-se liniile printate la scară pe o foaie de hârtie și lipită pe placă. În figura 11 dreapta se poate vedea modul în care au fost

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realizate găurile din capac, cu ajutorul unei bormașini cu coloană.



Fig. 12 Realizarea capacului prin metode clasice de prototipare

Al doilea prototip a fost realizat cu ajutorul unei freze dotate cu comandă numerică (fig. 13). Pentru realizarea programului mașina, a fost folosit programul Estlcam v13 și softul de control mașină Mach3 Mill (fig. 14).



Fig. 13 Freza CNC folosită

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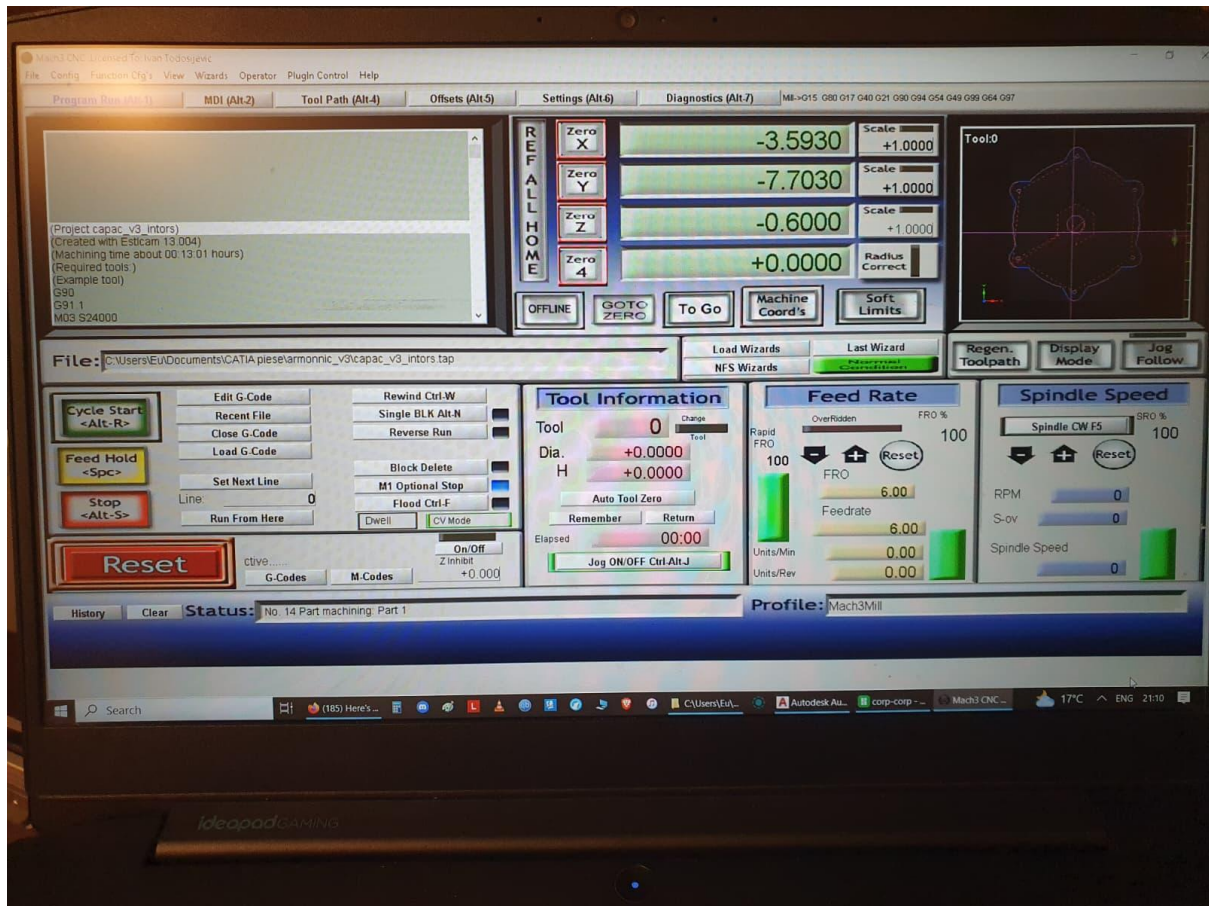


Fig. 14 Vedere din Mach3 Mill

6. Analiza structurală statică în programul Ansys

Analiza structurală statică s-a axat pe elementul deformabil pentru că acesta este supus celor mai puternice solicitări în timpul funcționării, dar și pentru că acesta este realizat din cel mai puțin rigid material, TPU. Pentru definirea materialului în ANSYS Mechanical s-a utilizat fișa tehnică a materialului (fig. 15).

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TECHNICAL INFORMATION:

Diameter:	1.75 mm or 2.85 mm
Diameter Tolerance:	+/- 0.05 mm
Avg Roundness:	+ 0.03 mm
Net Weight:	0.85 kg
Print Temperature:	200°C - 220°C
Bed Temperature:	50°C - 70°C



Physical Properties	Test Method	Unit	Typical Value
Specific Density	ASMT D792	g/cm ³	1.16
Hardness	Test Method	Unit	Typical Value
Shore A	ASTM D2240	-	91
Shore D	ASTM D2240	-	40
Shore D 15s	ASTM D2240	-	37
Mechanical Properties	Test Method	Unit	Typical Value
Tensile Strength:			
@ Break	ASTM D638	MPa	28
@ 5% Strain	ASTM D638	MPa	2
@ 10% Strain	ASTM D638	MPa	4
Elongation at break	ASTM D638	%	700
Flexular Modulus	ASTM D790	MPa	67
Thermal Properties	Test Method	Unit	Typical Value
Heat Distortion Temperature @ 0.45 MPa	ASTM D648	°C	70
Melting Temperature Tm	ASTM D3418	°C	157
Elastomer Properties	Test Method	Unit	Typical Value
Tear Strength	ASTM D1004	kN/m	115

Fig. 15 Extras din fișa tehnică a materialului TPU

În primă fază, am constrâns modelul 3D al elementului flexibil la bază, am fixat flancurile stângi ale dinților care intră în angrenare în timpul funcționării și am aplicat un moment pe suprafața cilindrică interioară. În urma rezolvării modelului matematic, s-au obținut următoarele rezultate. La 3 [Nm], reductorul suportă solicitarea statică fără deformări însemnate și stres acumulat la baza dinților (fig. 16).

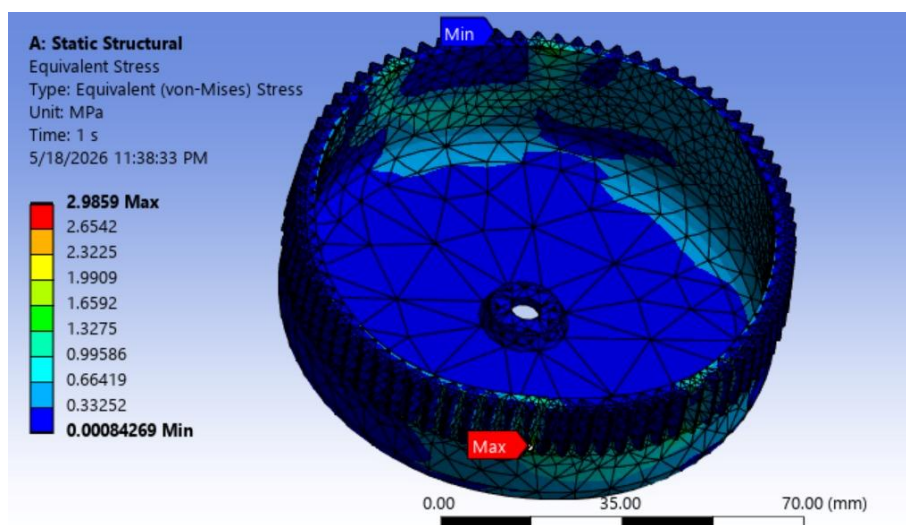


Fig. 16 Primul test

În continuare, am solicitat static elementul deformabil cu 25 [Nm]. Deformarea era vizibil crescută, însă forfecarea dinților era în continuare neglijabilă (fig. 17).

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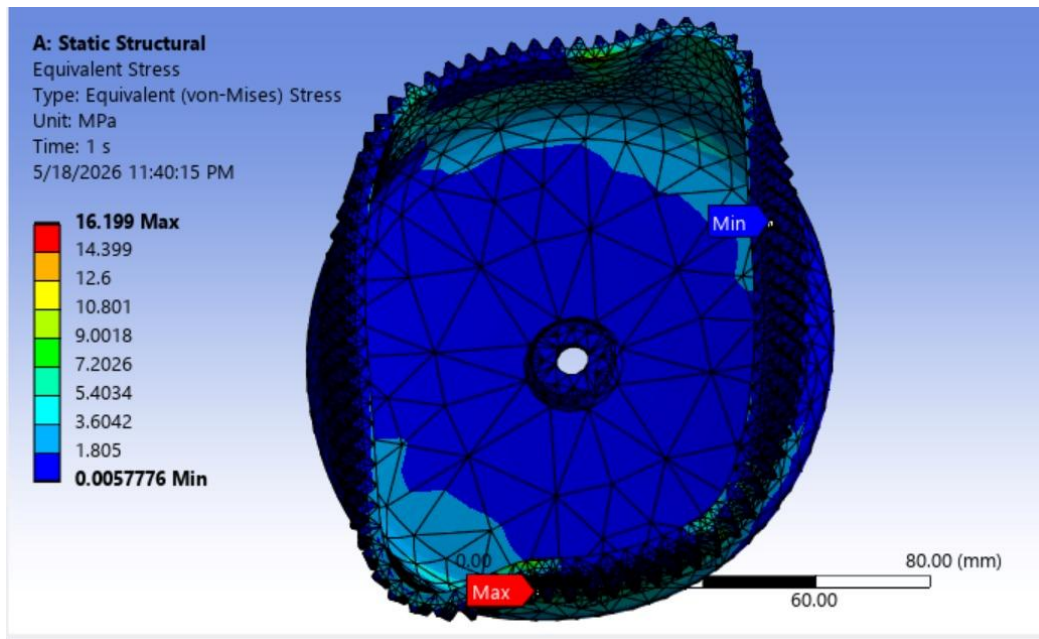


Fig. 17 Al doilea test

Pentru al treilea test, am constrâns dinții și am aplicat același moment pe suprafața cilindrică interioară. Abia acum s-a putut observa o solicitare la baza dinților însemnată.

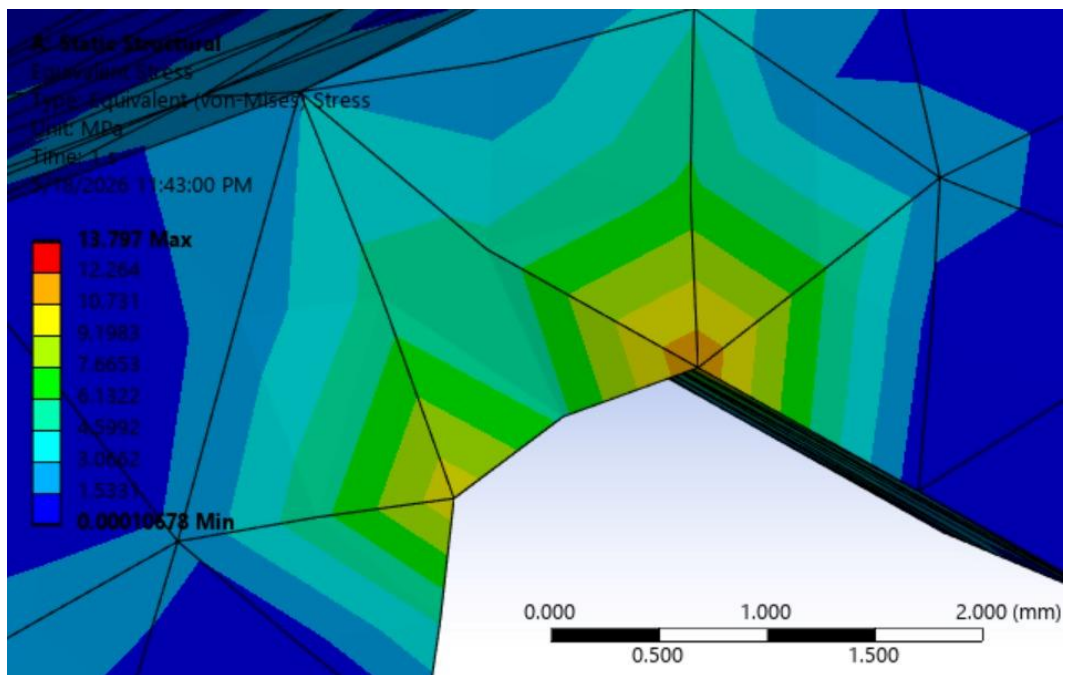


Fig. 18 Al treilea test

7. Concluzii

**PLASTIC MATERIAL INFLUENCE OVER THE GEOMETRICAL CHARACTERISTICS OF THE
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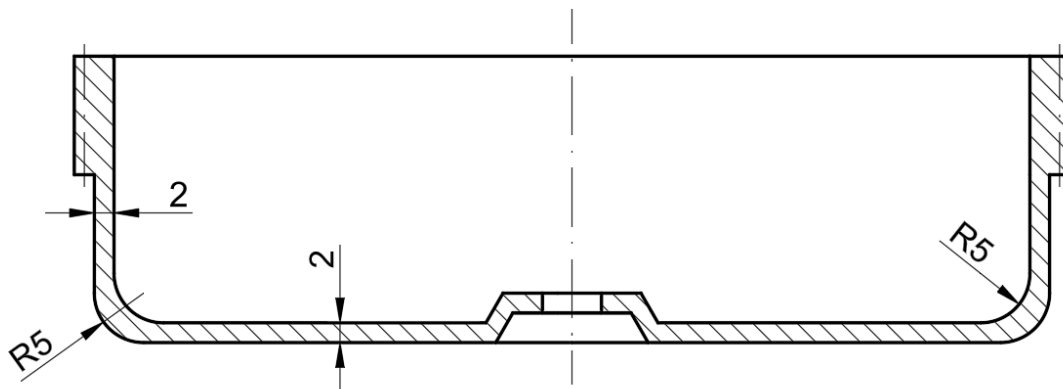


Fig. 19 Reprezentarea grafică a elementului deformabil testat: $z=80$, $m=1,25$

Elementul deformabil pentru care s-au realizat testele preliminare în ANSYS (fig. 19) rezistă la un moment static de până în 50 [Nm]. Contribuția originală a lucrării a fost adusă de testarea concretă a unui reductor armonic realizat prin manufacturare aditivă. Pentru continuarea cercetării, vom realiza și alte modele 3D pentru elementul deformabil.

8. Bibliografie

[1] Musser, W. C., „Strain wave gearing”, Statele Unite ale Americii, 1957 (US 2906143 A)

9. Notății

z – numărul de dinți

m – modulul roților dințate

STRUCTURAL ANALYSIS OF A 3D-PRINTED ROBOTIC GRIPPER USING FINITE ELEMENT METHOD

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ABSTRACT: This paper presents the structural analysis and iterative optimization of a 3D-printed robotic gripper manufactured from PLA. The gripper was designed in CATIA V5 and evaluated using ANSYS Static Structural. A custom PLA material was defined in Engineering Data, considering an equivalent density corresponding to a 50% infill configuration. The study was developed in three stages: the simulation of an initial solid geometry, the simulation of an optimized geometry with triangular and rectangular cut-outs, and a final verification case corresponding to the vertical load generated by a 1 kg object. The finite element model included steel pins in the joint areas, revolute joints to approximate bearing-like rotational connections, and an asymmetric bonded contact in the toothed transmission. The optimized design reduced the maximum equivalent stress under the same driving moment.

CUVINTE CHEIE: gripper robotic; analiză FEA; PLA; optimizare structurală; imprimare 3D.

1. Introducere

Lucrarea prezintă analiza structurală a unui gripper robotic proiectat pentru fabricare prin imprimare 3D. Ansamblul este alcătuit din brațe articulate, bacuri de prindere și o transmisie dințată care permite acționarea coordonată a celor două bacuri. Deși funcționarea cinematică este necesară pentru înțelegerea ansamblului, accentul lucrării este pus pe verificarea rezistenței componentelor, pe definirea modelului FEA și pe optimizarea formei pieselor în funcție de distribuția tensiunilor.

Modelul 3D a fost realizat în CATIA V5, iar simulările structurale au fost efectuate în ANSYS Static Structural. Într-o primă etapă, s-a analizat o variantă constructivă mai masivă, cu volum de material păstrat în majoritatea zonelor. Această variantă a avut rolul de a identifica zonele critice ale mecanismului sub acțiunea momentului introdus de servomotor. După interpretarea rezultatelor, geometria a fost optimizată prin introducerea unor goluri triunghiulare și dreptunghiulare, în funcție de spațiul disponibil și de forma elementelor.

În ultima etapă, modelul final a fost verificat pentru cazul unei încărcări echivalente cu greutatea unui obiect de 1 kg. Obiectivul principal este evaluarea comportării mecanice a gripperului imprimat 3D, urmărind tensiunile echivalente von Mises, deformațiile totale și influența modificărilor geometrice asupra distribuției solicitărilor. Lucrarea corelează modelul numeric cu condițiile de fabricare, prin definirea unui material PLA echivalent cu densitatea corespunzătoare unui infill de 50%.

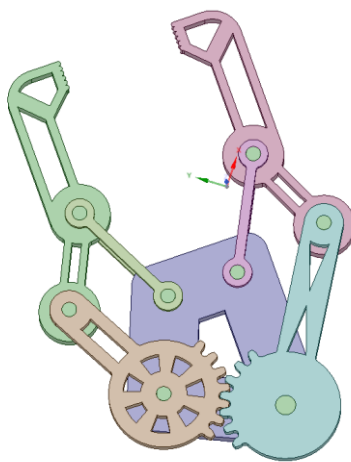


Fig. 1. Modelul 3D al gripperului robotic

2. Stadiul actual privind piesele printate 3D și analiza FEA

Piesele printate 3D sunt utilizate frecvent pentru prototipuri funcționale, mecanisme educaționale și componente cu solicitări moderate. PLA-ul este un material accesibil și ușor de imprimat, însă comportarea sa mecanică depinde puternic de parametrii de fabricație, precum procentul de umplere, orientarea piesei pe patul imprimantei, grosimea pereților și calitatea aderenței dintre straturi. Din acest motiv, analiza numerică a unei componente printate 3D trebuie interpretată ca o verificare orientativă, nu ca o validare completă a comportării reale.

În cazul unui gripper robotic, zonele cele mai solicitate sunt articulațiile, brațele de legătură, dantura roților și bacurile de prindere. În aceste regiuni pot apărea concentrări de tensiune, mai ales în apropierea găurilor, racordurilor și contactelor dintre elemente. Metoda elementelor finite permite identificarea zonelor critice și orientarea procesului de optimizare geometrică.

În această lucrare, analiza FEA nu a fost utilizată doar pentru verificarea finală a piesei, ci și ca instrument de dezvoltare a modelului. Rezultatele primei simulări au indicat zonele unde materialul putea fi eliminat fără afectarea semnificativă a rigidității globale. Astfel, forma finală a rezultat printr-un proces iterativ, în care modelarea CAD și simularea structurală au fost corelate.

Tabelul 1. Etapele principale ale dezvoltării modelului

Etapă	Mediu de lucru	Scop
Model inițial	CATIA V5	Realizarea unei geometrii mai masive, cu material păstrat în majoritatea zonelor
Simulare inițială	ANSYS Static Structural	Identificarea zonelor critice sub momentul de 1200 N·mm
Optimizare geometrică	CATIA V5	Introducerea golurilor triunghiulare și dreptunghiulare
Simulare optimizată	ANSYS Static Structural	Verificarea reducerii și uniformizării tensiunilor
Simulare finală 1 kg	ANSYS Static Structural	Verificarea comportării la greutatea unui obiect de 1 kg
Fabricare	Imprimare 3D PLA	Realizarea piesei cu infill de 50%

3. Modelul 3D și definirea materialului

Modelul geometric al gripperului a fost realizat în CATIA V5. Ansamblul include baza fixă, brațele de transmitere, roțile dințate, elementele articulate și bacurile de prindere. Modelul a fost pregătit astfel încât să poată fi exportat către ANSYS pentru analiza structurală și, ulterior, către slicer pentru imprimare 3D.

Prima variantă a fost realizată cu un volum mai mare de material, fără goluri de ușurare în elementele principale. Această abordare a fost aleasă pentru a obține o geometrie robustă inițială, pe baza căreia să fie identificate zonele cu tensiuni mari și zonele slab solicitate. După prima simulare, în regiunile cu solicitări reduse au fost introduse goluri de material. Golurile triunghiulare au fost utilizate în zonele unde forma piesei permitea o distribuție locală a materialului, iar golurile dreptunghiulare au fost introduse în brațele alungite, unde secțiunea permitea eliminarea materialului din zona centrală fără reducerea majoră a rezistenței la încovoiere.

Pentru analiza structurală, în ANSYS Engineering Data a fost definit un material custom corespunzător PLA-ului utilizat la imprimarea 3D. Deoarece modelul fizic urma să fie imprimat cu infill de 50%, densitatea introdusă în simulare a fost stabilită la o valoare echivalentă de 625 kg/m³. Această valoare reprezintă o aproximare a reducerii masei față de PLA-ul complet solid și permite o corelare mai bună între modelul numeric și piesa imprimată.

Tabelul 2. Proprietăți introduse pentru materialul PLA în ANSYS

Proprietate	Valoare	Unitate
Densitate echivalentă	625	kg/m ³
Modul Young	1.4	GPa
Coeficient Poisson	0.33	-

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Procent infill asociat	50	%
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Valorile au fost utilizate pentru o analiză comparativă între variantele constructive și pentru estimarea comportării la solicitări statice. Totuși, trebuie menționat că un material printat 3D nu se comportă perfect omogen și izotrop, deoarece proprietățile reale depind de orientarea straturilor, tipul de infill și parametrii de imprimare.

4. Definirea modelului FEA

Analiza structurală a fost realizată în ANSYS Static Structural. Pentru a aproxima cât mai corect funcționarea ansamblului, modelul FEA nu a fost tratat ca o singură piesă rigidizată artificial, ci ca un ansamblu format din elemente conectate în zonele de articulație. În locul șuruburilor au fost introduse tije de oțel, care permit definirea mai realistă a legăturilor dintre componente.

Articulațiile mecanismului au fost simulate prin revolute joints, pentru a aproxima comportarea unor lagăre sau rulmenți idealizați. Astfel, piesele pot avea rotație relativă în jurul axelor definite, fără a fi blocate complet prin contacte rigide de tip bonded. Rotația a fost definită între suprafața interioară a găurii piesei și peretele exterior al tijei de oțel. Această abordare este mai potrivită pentru un mecanism articulat, deoarece nu transformă legăturile mobile în îmbinări complet rigide.

În zona danturii roților a fost utilizat un contact bonded asymmetric, cu scopul de a aproxima transmiterea eforturilor prin angrenare. Această simplificare permite stabilizarea modelului numeric și transmiterea momentului între roțile dințate, fără a introduce complexitatea unui contact neliniar complet între dinți. În interpretarea rezultatelor trebuie ținut cont că această ipoteză poate conduce la o rigidizare locală a zonei de angrenare, însă permite compararea coerentă a celor două iterații constructive.

Discretizarea modelului a fost realizată printr-un mesh global cu dimensiunea elementului de 4 mm. În zona contactului dintre dinți, unde se așteptau variații locale mai mari ale tensiunii, s-a aplicat o rafinare locală a rețelei, cu dimensiunea elementului de 0.5 mm. Această rafinare a fost necesară deoarece dantura reprezintă o zonă critică, cu geometrie complexă și concentrări locale de tensiune.

Tabelul 3. Setările principale ale modelului FEA

Parametru FEA	Valoare / metodă
Tip analiză	Static Structural
Material piese printate	PLA custom
Densitate PLA	625 kg/m ³
Elemente de legătură	Tije de oțel în zonele șuruburilor
Articulații	Revolute joints
Contact dantură	Bonded asymmetric
Mesh global	4 mm
Mesh local dantură	0.5 mm
Rezultate urmărite	Deformație totală, tensiune echivalentă von Mises

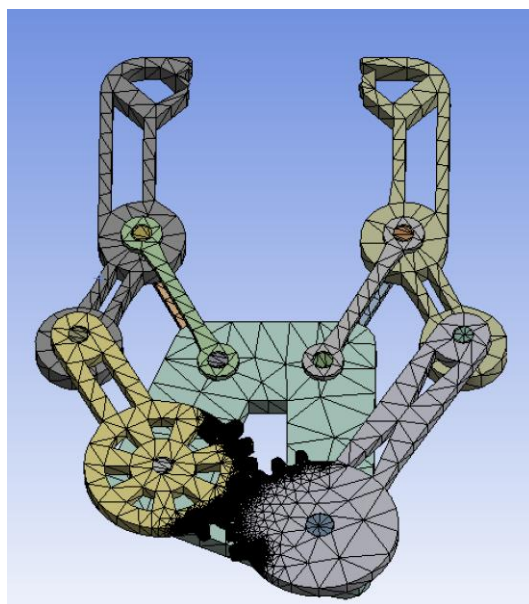


Fig. 2. Modelul FEA cu tije de oțel și articulații de tip revolute joint

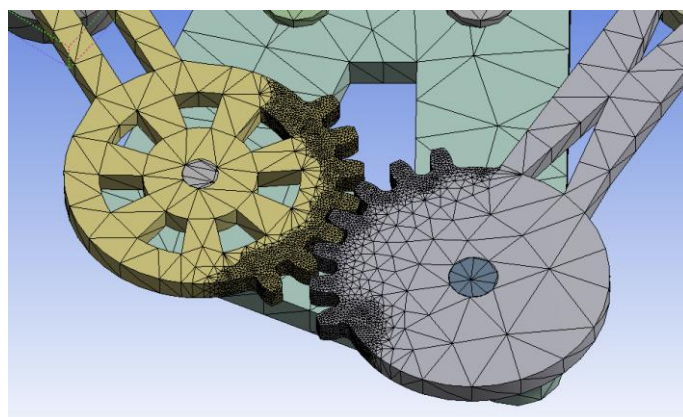


Fig. 3. Rafinarea locală a discretizării în zona danturii

5. Simularea 1 - modelul inițial cu volum de material ridicat

Prima simulare a fost realizată pe modelul inițial, în care elementele principale aveau un volum de material mai mare și nu conțineau goluri de ușurare. Scopul acestei etape a fost identificarea zonelor critice ale ansamblului sub acțiunea momentului introdus de servomotor.

Momentul aplicat a fost de 1200 N·mm, valoare utilizată pentru verificarea comportării mecanismului în cazul acționării prin servomotor. Această solicitare a permis observarea traseului principal al eforturilor și localizarea zonelor în care apar concentrări de tensiune.

$$M = 1200N \cdot mm \quad (1)$$

În urma simulării, tensiunea echivalentă von Mises maximă a fost de 33.5 MPa, fiind localizată în jurul danturii. Această distribuție era de așteptat, deoarece dantura reprezintă zona prin care se transmite momentul de acționare între elementele mecanismului. Deformația maximă a fost de aproximativ 0.7 mm, ceea ce indică o rigiditate globală acceptabilă pentru ansamblu.

Analiza câmpului de tensiuni a arătat că anumite regiuni ale piesei erau slab sollicitate, în timp ce zona danturii concentra o parte importantă din eforturi. Acest rezultat a justificat trecerea la o a doua iterație geometrică, în care materialul a fost eliminat din zonele cu solicitări reduse.

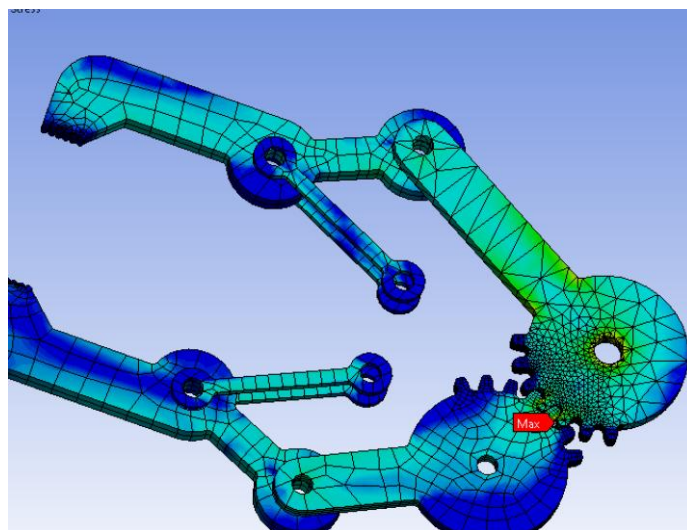


Fig. 4. Distribuția tensiunilor pentru modelul inițial al griperului

6. Simularea 2 - modelul optimizat cu goluri de ușurare

Pe baza rezultatelor obținute în prima simulare, modelul a fost modificat în CATIA V5. Optimizarea a constat în introducerea unor goluri triunghiulare și dreptunghiulare în elementele mecanismului. Forma golurilor a fost aleasă în funcție de geometria locală: golurile triunghiulare au fost utilizate în zonele mai compacte sau apropiate de roți, iar golurile dreptunghiulare au fost utilizate în brațele alungite.

A doua simulare a fost realizată folosind aceleași condiții principale ca în prima etapă, pentru ca rezultatele să poată fi comparate direct. Momentul aplicat a rămas 1200 N·mm, iar modelarea articulațiilor și a danturii a fost păstrată în același mod, prin tije de oțel, revolute joints și contact bonded asymmetric în zona angrenării.

$$M = 1200N \cdot mm \quad (1)$$

În această iterație, tensiunea maximă von Mises a scăzut la 26.5 MPa, valoarea maximă fiind localizată tot în zona danturii. Reducerea tensiunii maxime arată că modificarea geometriei nu a slăbit mecanismul, ci a condus la o distribuție mai favorabilă a eforturilor. În plus, tensiunea s-a dispersat mai bine în restul ansamblului, ceea ce indică o utilizare mai eficientă a materialului.

Deformația maximă a rămas aproximativ 0.7 mm, similară cu cea obținută pentru modelul inițial. Acest rezultat este important deoarece arată că reducerea volumului de material nu a produs o scădere semnificativă a rigidității globale.

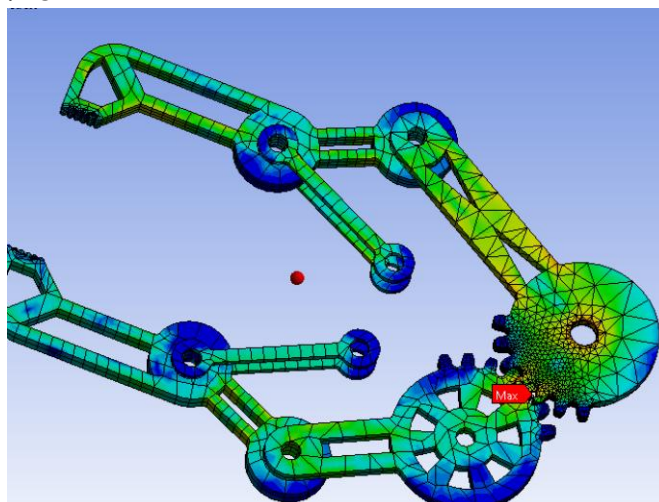


Fig. 5. Distribuția tensiunilor pentru modelul optimizat cu goluri de ușurare

7. Interpretarea scăderii tensiunii după optimizare

La prima vedere, scăderea tensiunii după eliminarea materialului poate părea contraintuitivă. Totuși, în analiza structurală nu contează doar cantitatea totală de material, ci și poziția acestuia și modul în care eforturile sunt transmise prin piesă. În modelul inițial, materialul în exces din zone slab solícitate nu contribuia eficient la rezistența ansamblului și putea produce rigidizări locale care favorizau concentrarea tensiunilor în jurul danturii.

Prin introducerea golurilor, traseul de transmitere a eforturilor s-a modificat, iar materialul rămas a lucrat mai uniform. Astfel, tensiunea nu s-a mai concentrat într-o zonă atât de restrânsă, ci s-a distribuit pe o parte mai mare a ansamblului. Optimizarea nu a urmărit doar reducerea masei, ci și îmbunătățirea distribuției solícităților.

$$\Delta\sigma = \sigma_1 - \sigma_2 = 7.0\text{Mpa} \quad (2)$$

$$\Delta\sigma = 33.5 - 26.5 = 7.0\text{Mpa}$$

$$\frac{33.5-26.5}{33.5} \cdot 100 \approx 20.9\% \quad (3)$$

Rezultatul indică o reducere de aproximativ 20.9% a tensiunii maxime. Totuși, interpretarea trebuie făcută cu prudență, deoarece valorile locale din zona danturii pot fi influențate de rafinarea mesh-ului, de ipoteza de contact bonded asymmetric și de diferențele geometrice dintre cele două variante. Din acest motiv, concluzia corectă este că rezultatele indică o distribuție mai favorabilă a tensiunilor pentru varianta optimizată.

8. Simularea 3 - verificarea modelului final pentru obiect de 1 kg

După stabilirea formei finale a gripperului, s-a realizat o simulare suplimentară pentru verificarea comportării structurale la susținerea unui obiect de 1 kg. Această simulare nu urmărește transmiterea momentului prin servomotor, ci răspunsul structural al bacurilor și al brațelor atunci când obiectul prins exercită o încărcare verticală.

Greutatea obiectului a fost calculată cu relația:

$$G = m \cdot g \quad (4)$$

Pentru un obiect cu masa de 1 kg rezultă:

$$G = 1 \cdot 9.81 = 9.81 \text{ N}$$

În ipoteza unei distribuții simetrice a sarcinii pe cei doi bacuri, încărcarea a fost împărțită în mod egal. În ANSYS s-a aplicat o forță verticală de 5 N pe fiecare bac, orientată în jos, reprezentând aproximarea greutății totale a obiectului de 1 kg.

$$F_{bac} = \frac{G}{2} = \frac{9.81}{2} \approx 5\text{N} \quad (5)$$

În această simulare, deformația maximă a fost de 7.3 mm, localizată în vârful bacurilor. Această valoare este explicabilă deoarece bacurile sunt elementele cele mai îndepărtate de zona fixă și au braț de pârghie mare față de articulațiile mecanismului. Tensiunea echivalentă von Mises maximă a fost de 11.9 MPa, localizată la brațele de legătură cu elementul fix.

Rezultatul arată că, pentru încărcarea echivalentă unui obiect de 1 kg, tensiunea maximă rămâne sub valorile utilizate orientativ pentru PLA în aplicații printate 3D. Prin urmare, testul poate fi considerat trecut cu succes pentru scopul demonstrativ al gripperului.

STRUCTURAL ANALYSIS OF A 3D-PRINTED ROBOTIC GRIPPER USING FINITE ELEMENT METHOD

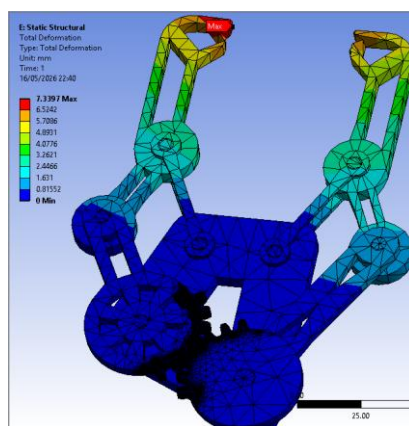


Fig. 6. Deformația totală pentru simularea încărcării echivalente unui obiect de 1 kg

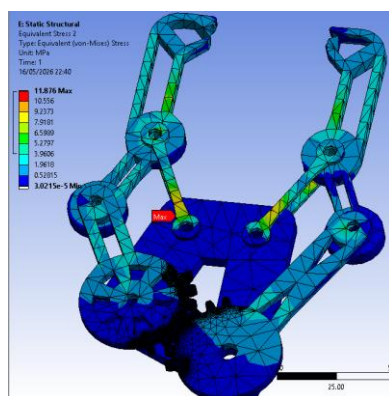


Fig. 7. Tensiunea echivalentă von Mises pentru simularea încărcării de 1 kg

9. Compararea rezultatelor celor trei simulări

Tabelul 4. Comparația rezultatelor FEA

Simulare	Model analizat	Solicitare	Tensiune maximă von Mises	Deformație maximă	Zona critică
Simularea 1	Model inițial, volum ridicat	Moment 1200 N·mm	33.5 MPa	~0.7 mm	Dantură
Simularea 2	Model optimizat, cu goluri	Moment 1200 N·mm	26.5 MPa	~0.7 mm	Dantură
Simularea 3	Model final	5 N pe fiecare bac	11.9 MPa	7.3 mm	Brațe de legătură / vârf bacuri

Rezultatele evidențiază rolul procesului iterativ de proiectare. Prima simulare a permis identificarea danturii ca zonă critică și a arătat că unele zone ale modelului inițial erau slab solicitate. După introducerea golurilor de ușurare, tensiunea maximă s-a redus de la 33.5 MPa la 26.5 MPa, iar deformația totală a rămas aproximativ constantă. Astfel, modelul optimizat oferă un raport mai bun între volum, masă și comportare structurală.

Simularea finală, corespunzătoare unui obiect de 1 kg, a produs o tensiune maximă mai mică, de 11.9 MPa, dar o deformație mai mare, de 7.3 mm, localizată în vârful bacurilor. Acest comportament este specific încărcărilor aplicate la capătul unor elemente alungite, unde deplasarea poate fi mai mare chiar dacă tensiunea rămâne acceptabilă.

10. Fabricarea prin imprimare 3D

După validarea numerică a modelului final, gripperul a fost pregătit pentru imprimare 3D din PLA.

Pentru a corela modelul fizic cu densitatea introdusă în ANSYS, piesele au fost realizate cu un infill de 50%. Această alegere corespunde aproximativ densității echivalente de 625 kg/m^3 utilizate în Engineering Data.

În cazul pieselor funcționale printate 3D, procentul de infill nu este singurul parametru important. Rezistența depinde și de numărul de pereți, orientarea pieselor pe patul imprimantei, temperatura de extrudare și calitatea legăturii dintre straturi. Pentru gripper, zonele de articulație și dantura sunt cele mai sensibile, motiv pentru care piesele au fost proiectate cu grosimi suficiente în jurul găurilor și cu material păstrat în zonele de transmitere a eforturilor.

Fabricarea modelului permite verificarea practică a asamblării, a jocurilor dintre elemente și a funcționării articulațiilor. Totuși, validarea completă a comportării mecanice ar necesita testarea experimentală a gripperului imprimat, prin aplicarea unor sarcini cunoscute și compararea deformațiilor măsurate cu cele obținute numeric.

11. Concluzii

Lucrarea a prezentat analiza structurală și optimizarea unui gripper robotic realizabil prin imprimare 3D din PLA. Modelul a fost dezvoltat în CATIA V5 și analizat în ANSYS Static Structural, folosind un material PLA custom cu densitate echivalentă pentru infill de 50%.

Prima simulare, realizată pe modelul inițial cu volum ridicat de material, a evidențiat o tensiune maximă de 33.5 MPa, localizată în zona danturii, și o deformare maximă de aproximativ 0.7 mm. Pe baza distribuției tensiunilor, modelul a fost optimizat prin introducerea unor goluri triunghiulare și dreptunghiulare. A doua simulare a arătat o scădere a tensiunii maxime la 26.5 MPa, cu menținerea unei deformații maxime apropiate de 0.7 mm, ceea ce confirmă eficiența optimizării.

Modelul final a fost verificat suplimentar pentru cazul unei încărcări echivalente cu greutatea unui obiect de 1 kg. În această situație, tensiunea maximă a fost de 11.9 MPa, iar deformația maximă de 7.3 mm, localizată în vârful bacurilor. Rezultatele indică faptul că gripperul poate susține această încărcare în condițiile ipotezelor de simulare utilizate.

O contribuție importantă a lucrării constă în modul de definire a modelului FEA: utilizarea tijelor de oțel în zonele de șuruburi, introducerea revolute joints pentru aproximarea articulațiilor și rafinarea mesh-ului în zona danturii. Aceste aspecte permit o reprezentare mai realistă a comportării ansamblului față de o modelare complet rigidizată prin contacte bonded.

Cercetările viitoare pot include măsurarea experimentală a forței reale de prindere, testarea deformației bacurilor sub sarcină, compararea mai multor orientări de printare și utilizarea unor materiale mai rezistente, precum PETG, ABS sau nylon ranforsat.

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13. Notății

M = moment aplicat de servomotor [$\text{N}\cdot\text{mm}$];
G = greutatea obiectului [N];
m = masa obiectului [kg];
g = accelerația gravitațională [m/s^2];
F_{bac} = forța aplicată pe fiecare bac [N];
 σ_{vM} = tensiunea echivalentă von Mises [MPa];
u_{max} = deformația totală maximă [mm];
E = modulul de elasticitate longitudinală [GPa];
v = coeficientul lui Poisson [-].

SMART ARMOR 2.0: INTELLIGENT IMPACT PROTECTION MATERIALS BASED ON NON-NEWTONIAN FLUIDS

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SUMMARY: This paper presents the fabrication and impact analysis of a smart GFRP composite structure with an internal TPU insert filled with a non-Newtonian STF based on PEG400 and Aerosil 200 SiO₂. The plates were manufactured by hand lay-up using twill glass fiber and epoxy resin, in a sandwich configuration consisting of 10 lower GFRP layers, a TPU-STF capsule, and 10 upper GFRP layers. Two STF compositions were prepared, containing 20 wt.% and 25 wt.% SiO₂. Impact tests at 20 J showed a reduction of approximately 17% in maximum impact force compared with the simple GFRP laminate. The STF-containing samples exhibited a longer contact duration and no perforation of the lower face, while the reference GFRP sample showed local perforation.

KEYWORDS: GFRP; shear-thickening fluid; TPU capsule; low-velocity impact; energy absorption.

1. Introducere

Structurile laminate cu fibră de sticlă sunt utilizate în aplicații unde sunt necesare masă redusă, rezistență mecanică și rigiditate. În cazul solicitărilor de impact cu viteză redusă, laminatele GFRP pot suferi deteriorări locale precum fisurarea matricei, delaminarea dintre straturi, ruperea fibrelor și perforarea locală [2].

Această lucrare propune realizarea și testarea unei structuri compozite inteligente de tip GFRP/TPU-STF/GFRP, comparată cu un laminat GFRP simplu. Structura propusă integrează o capsulă flexibilă din TPU umplută cu lichid non-newtonian cu îngroșare la forfecare. Lichidul STF este alcătuit din PEG400 și particule de SiO₂ Aerosil 200.

Scopul principal este evaluarea influenței inserției TPU-STF asupra comportamentului la impact. Comparăția principală a fost realizată la energia de 20 J, între placa GFRP simplă și plăcile GFRP/TPU-STF cu două concentrații de SiO₂: 20 wt.% și 25 wt.%. De asemenea, s-au realizat încercări și cu o energie de 60 J pentru analiza răspunsului probelor cu STF la solicitări mai ridicate.

2. Stadiul actual

În structurile compozite laminate, impactul cu viteză redusă produce mecanisme de cedare diferite față de materialele metalice. Energia este disipată prin deformarea plăcii, fisurarea matricei, delaminare, ruperea fibrelor și, la solicitări severe, perforare [2]. Comportamentul la impact al plăcilor GFRP depinde de mai mulți factori, precum grosimea laminatului, numărul de straturi, tipul țesăturii, orientarea fibrelor, proprietățile matricei epoxidice, energia de impact, forma impactorului și condițiile de sprijin ale probei [2]. În general, creșterea grosimii laminatului poate îmbunătăți rezistența la impact, însă această soluție conduce și la creșterea masei structurii. Din acest motiv, o direcție actuală de cercetare este dezvoltarea unor structuri compozite capabile să ofere protecție locală la impact, fără adăugarea uniformă de material pe întreaga suprafață.

Fluidele cu îngroșare la forfecare sunt suspensii concentrate care își cresc vâscozitatea aparentă atunci când sunt supuse unei solicitări rapide. În suspensiile pe bază de SiO₂ și polietilenglicol, comportamentul este asociat cu formarea temporară a aglomerărilor hidrodinamice și cu apariția contactelor particulă-particulă activate de solicitarea mecanică [3], [4].

În majoritatea studiilor existente, lichidele STF au fost utilizate predominant prin impregnarea materialelor textile sau a țesăturilor flexibile, în special pentru aplicații de protecție la impact, înțepare

sau solicitări dinamice [1], [6]. În aceste cazuri, lichidul pătrunde între fibrele textile și modifică răspunsul mecanic al țesăturii. Totuși, această abordare este specifică materialelor flexibile, unde deformarea țesăturii permite activarea ușoară a lichidului în timpul solicitării.

Utilizarea unui lichid STF încapsulat și introdus într-o structură rigidă de tip GFRP este mult mai puțin abordată în literatura consultată. O astfel de soluție este diferită de impregnarea textilă, deoarece lichidul nu este distribuit între fibre, ci este păstrat în stare liberă într-o capsulă flexibilă, poziționată local în interiorul laminatului. Această configurație permite separarea lichidului de matricea epoxidică și concentrarea efectului de protecție în zona expusă impactului [7].

3. Materiale și metode

Structura compozită a fost realizată prin laminare manuală, utilizând fibră de sticlă twill, rășină bicomponentă epoxidică BK, folie TPU cu o grosime de 15 μm , PEG400 și Aerosil 200. Formele utilizate au fost din silicon, cu dimensiuni de aproximativ $300 \times 200 \text{ mm}$, din care se pot fabrica 4 probe de $150 \times 100 \text{ mm}$.

Rășina epoxidică a fost preparată prin amestecarea componentelor A și B în raport masic 100:60, timp de aproximativ 1 minut. Lichidul STF a fost preparat prin adăugarea treptată a particulelor de SiO_2 în PEG400, urmată de amestecare mecanică la 500-750 rpm, timp de 1,5-2 h, etapă necesară pentru obținerea dispersiei uniforme. [1]

Capsulele cu dimensiuni de $90 \times 60 \text{ mm}$ au fost fabricate prin termosigilarea a trei laturi ale foliei TPU. După introducerea lichidului STF, latura deschisă a fost sigilată, iar excesul de folie a fost tăiat. Suprafețele capsulelor au fost șlefuite cu hârtie abrazivă de granulație 600 și degresate cu alcool izopropilic pentru creșterea aderenței la matricea epoxidică.

Placa GFRP/TPU-STF/GFRP a fost realizată prin aplicarea succesivă a straturilor de fibră de sticlă și rășină. După primele 10 straturi, s-a așteptat aproximativ 20 min pentru ca rășina să devină mai vâscoasă. Capsula TPU-STF a fost poziționată în zona centrală a fiecărei plăci, apoi au fost laminate încă 10 straturi de fibră de sticlă. Structura a fost presată cu o greutate și lăsată la întărire.



Fig. 1. Pregătirea plăcii de GFRP

Au fost testate trei categorii principale de probe. Prima categorie a fost GFRP-REF, reprezentând laminatul GFRP simplu, fără inserție TPU-STF, utilizat ca probă martor. A doua categorie a fost GFRP/STF-20, alcătuită dintr-o structură GFRP/TPU-STF cu lichid shearthickening având 20 wt.% SiO_2 , utilizată pentru analizarea comportamentului la o concentrație redusă de particule. A treia categorie a fost GFRP/STF-25, alcătuită dintr-o structură GFRP/TPU-STF cu lichid shear-thickening având 25 wt.% SiO_2 , utilizată pentru analizarea comportamentului la o concentrație mai ridicată de

particule.

Concentrația masică a dioxidului de siliciu a fost calculată cu relația:

$$w_{SiO_2} = \frac{m_{SiO_2}}{m_{SiO_2} + m_{PEG400}} \cdot 100 \quad (1)$$

Pentru proba STF-25:

$$w_{SiO_2} = 25\% \quad (2)$$

Pentru proba STF-20:

$$w_{SiO_2} = 20\% \quad (3)$$

Reducerea procentuală a forței maxime față de proba GFRP simplă a fost calculată cu relația:

$$RF = \frac{F_{max,GFRP} - F_{max,STF}}{F_{max,GFRP}} \cdot 100 \quad (4)$$

4. Rezultate experimentale și discuții

4.1. Rezultate experimentale la 20 J

Comparația principală a fost realizată la energia de 20 J, între probele GFRP simple și probele cu inserție TPU-STF. Graficele experimentale au fost de tip forță-timp, iar forța a fost exprimată în N. Pentru interpretarea rezultatelor, valorile de vârf au fost convertite și în kN.

Tabelul 1. Rezultate experimentale pentru încercările la 20 J

Probă	Structură	F_{max} [kN]	Timp la F_{max} [ms]	Durață contact [ms]
GFRP-1	GFRP simplu	9,14	2,499	5,322
GFRP-2	GFRP simplu	7,50	2,180	4,599
STF-20-1	GFRP/TPU-STF 20 wt. %	6,63	2,698	5,754
STF-20-2	GFRP/TPU-STF 20 wt. %	7,12	2,306	5,430
STF-25-1	GFRP/TPU-STF 25 wt. %	7,28	2,343	5,604
STF-25-2	GFRP/TPU-STF 25 wt. %	6,50	2,660	6,139

Forța maximă medie pentru laminatul GFRP simplu a fost:

$$F_{max,GFRP} = 8.32kN$$

Pentru probele cu 20 wt.% SiO₂, forța maximă medie a fost:

$$F_{max,STF20} = 6.87kN$$

Reducerea procentuală a forței maxime față de proba GFRP simplă a fost calculată cu relația:

$$RF = \frac{F_{max,GFRP} - F_{max,STF20}}{F_{max,GFRP}} \cdot 100 \quad (5)$$

Rezultă o reducere a forței maxime de:

$$RF = \frac{8.32 - 6.87}{8.32} \cdot 100 = 17.43\% \quad (6)$$

Pentru probele cu 25 wt.% SiO₂, forța maximă medie a fost:

$$F_{max,STF25} = 6.89kN$$

Reducerea forței maxime este:

$$RF = \frac{8.32 - 6.89}{8.32} \cdot 100 = 17.19\% \quad (7)$$

Rezultatele experimentale evidențiază diferențe clare între laminatul GFRP simplu și structurile cu inserție TPU-STF. Probele GFRP simple au înregistrat cele mai mari valori ale forței maxime, respectiv 9,14 kN pentru GFRP-1 și 7,50 kN pentru GFRP-2, cu o medie de 8,32 kN. În comparație, probele cu STF au prezentat valori mai reduse ale forței maxime: 6,63 kN și 7,12 kN pentru STF-20, respectiv 7,28 kN și 6,50 kN pentru STF-25. Astfel, forța maximă medie s-a redus la 6,87 kN pentru STF-20 și 6,89 kN pentru STF-25, ceea ce corespunde unei reduceri de aproximativ 17% față de laminatul GFRP simplu.

Diferența dintre cele două concentrații de SiO₂ este redusă din punctul de vedere al forței maxime, însă devine mai evidentă la analiza duratei de contact. Laminatul GFRP simplu a avut o durată medie de contact de 4,961 ms, în timp ce probele STF-20 au avut o durată medie de 5,592 ms, iar probele STF-25 au ajuns la 5,872 ms. Creșterea duratei de contact indică faptul că impactul a fost transmis mai progresiv prin structurile cu TPU-STF, reducând intensitatea maximă a solicitării. Proba STF-25-2 a înregistrat cea mai mare durată de contact, 6,139 ms, asociată cu una dintre cele mai mici valori ale forței maxime, 6,50 kN, ceea ce arată un comportament mai amortizant al structurii.

Timpul la care apare forța maximă este relativ apropiat pentru toate probele, situându-se între 2,180 ms și 2,698 ms. Totuși, după atingerea vârfului de forță, curbele probelor cu TPUSTF scad mai lent, ceea ce arată o disipare a energiei pe un interval mai lung. Prin urmare, inserția TPU-STF nu modifică doar valoarea maximă a forței, ci și modul în care impactul este preluat și distribuit în timp.

4.2. Interpretarea structurală a probelor la 20 J

Probele GFRP simple au dezvoltat forțe maxime mai mari și au prezentat perforare locală în zona de impact. Acest comportament indică o concentrare locală a solicitării și o cedare mai severă a laminatului, aspecte vizibile în graficul din Fig. 2.

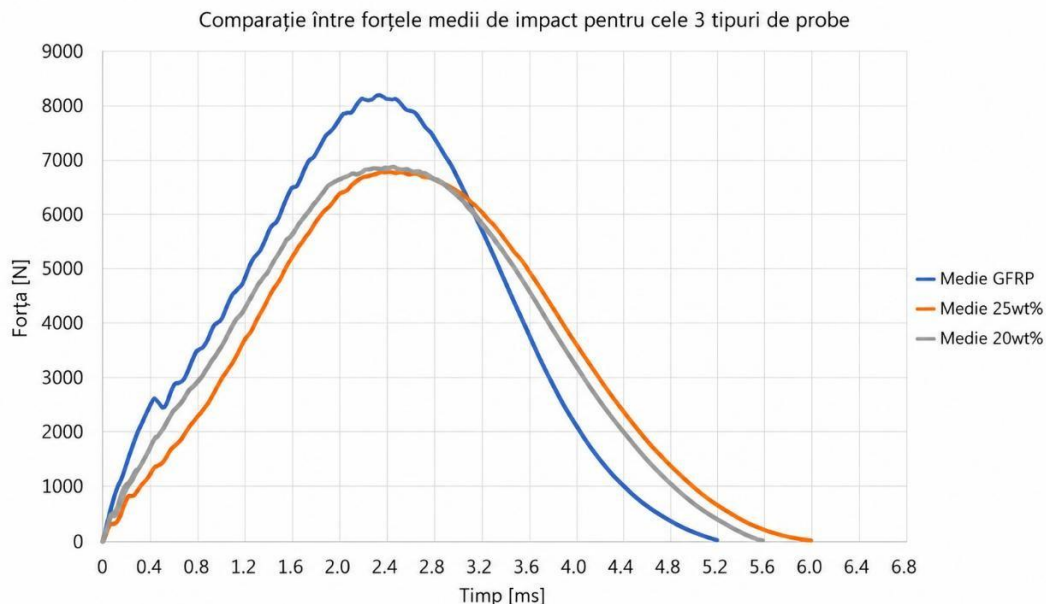


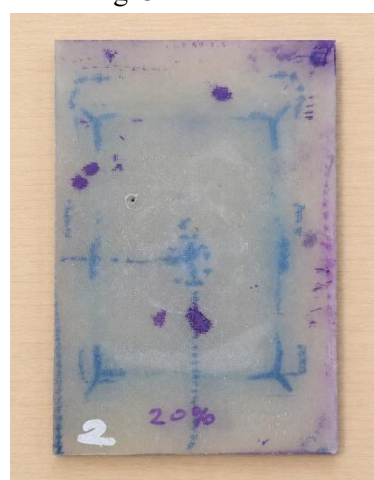
Fig. 2: Curbele medii forță–timp pentru laminatul GFRP de referință și structurile GFRP/TPU-STF cu 20 wt.% și 25 wt.% SiO₂, testate la 20 J

Probele GFRP/STF au dezvoltat forțe maxime mai mici și durate de contact mai mari. În plus, observațiile vizuale au evidențiat faptul că forța nu a perforat fața inferioară a probelor cu inserție STF. În cazul probei cu 20 wt.% SiO₂, zona de impact este vizibil deformată, însă partea inferioară a plăcii rămâne neperforată. Această observație este corelată cu datele măsurate: forța maximă este mai mică, iar contactul este mai îndelungat.

Deplasarea mai mare înregistrată la unele probe cu STF nu reprezintă o cedare structurală critică, deoarece nu a fost însoțită de perforarea feței inferioare. Această comportare indică o deformare controlată. Energia impactului este distribuită prin deformarea laminatului, deformarea capsulei TPU și răspunsul dependent de viteză al lichidului STF, aspect ce se observă în Fig. 3.



a)



b)

Fig. 3. Observații post-impact la 20 J:

- a) placă GFRP simplă cu perforare locală;
- b) placă GFRP/TPU-STF 20 wt.% SiO₂, cu deformare locală fără perforarea feței inferioare.

4.3. Comparația între STF-20 și STF-25 la 20 J

Concentrațiile de 20 wt.% și 25 wt.% SiO₂ au condus la valori medii foarte apropiate ale forței maxime: 6.87 kN pentru STF-20 și 6.89 kN pentru STF-25. Diferența principală se observă în durata contactului. Probele STF-25 au avut o durată medie de contact mai mare, de 5.872 ms, comparativ cu 5.592 ms pentru STF-20. Această diferență sugerează că suspensia cu fracție mai mare de SiO₂ prelungește răspunsul structurii în timpul impactului.

Din punct de vedere tehnologic, STF-20 a fost mai ușor de amestecat și introdus în capsulă cu mijloacele disponibile. Din punct de vedere al răspunsului la impact, STF-25 a avut o durată de contact mai mare dar o procesabilitate mai dificilă. Astfel, STF-20 oferă un avantaj de procesabilitate, iar STF-25 oferă un răspuns mai prelungit în timpul impactului.

4.4. Analiza suplimentară a plăcilor testate la 60 J

Probele au fost utilizate pentru analizarea comportamentului structurilor GFRP/TPUSTF la solicitare ridicată. În această serie au fost analizate probe cu 20 wt.% SiO₂ și 25 wt.% SiO₂.

Tabelul 2. Rezultate pentru probele suplimentare testate la 60 J

Probă	Structură	F_{max} [kN]	Timp la F_{max} [ms]	Deplasare maximă [mm]	Durată contact [ms]
STF-20-60J-1	GFRP/TPU-STF 20 wt. %	9,57	2,002	1,82	6,714
STF-20-60J-2	GFRP/TPU-STF 20 wt. %	9,75	1,828	1,69	6,746
STF-25-60J-1	GFRP/TPU-STF 25 wt. %	9,90	1,987	1,97	6,250
STF-25-60J-2	GFRP/TPU-STF 25 wt. %	9,96	2,087	7,11	6,422

Probele STF-20 din seria suplimentară au avut un răspuns repetabil, cu forțe maxime de 9.57 kN și 9.75 kN, iar durata de contact a fost de aproximativ 6.7 ms. Probele STF-25 au avut forțe maxime apropiate, de 9.90 kN și 9.96 kN.

Proba STF-25-60J-2 a prezentat o deplasare maximă de 7.11 mm, menținând în același timp forța maximă la aproximativ 10 kN. Acest comportament indică faptul că, la solicitare mai ridicată, structura GFRP/TPU-STF răspunde prin creșterea deformării, nu printr-o creștere abruptă a forței maxime. Din punct de vedere structural, acest răspuns este favorabil pentru disiparea progresivă a energiei.

Comparativ cu rezultatele de la 20 J, seria suplimentară arată că structurile cu STF pot menține un răspuns controlat și la solicitări mai intense. Forța maximă crește față de testele de 20 J, dar rămâne într-un domeniu apropiat pentru probele cu 20 wt.% și 25 wt.% SiO₂. Diferența majoră apare la nivelul deplasării maxime, ceea ce evidențiază rolul deformării controlate în absorbția impactului.

6. Concluzii

Lucrarea a urmărit realizarea unui compozit GFRP mai ușor, mai flexibil și capabil să ofere protecție locală la impact, fără creșterea uniformă a grosimii întregului laminat. Ideea principală a fost introducerea unui material activ doar în zona solicitată, prin integrarea unei capsule TPU umplute cu lichid non-newtonian STF. Astfel, structura propusă combină rigiditatea laminatului GFRP cu

capacitatea lichidului STF de a răspunde la solicitări rapide.

Contribuția originală a lucrării constă în integrarea lichidului STF în stare liberă, încapsulat într-o membrană flexibilă din TPU, în interiorul unei structuri rigide GFRP. Această abordare diferă de soluțiile clasice întâlnite în literatura de specialitate, unde STF-ul este utilizat în principal pentru impregnarea materialelor textile. În cazul de față, lichidul este păstrat ca inserție locală, ceea ce permite deformarea capsulei la impact și activarea comportamentului de îngroșare la forfecare în zona centrală a plăcii.

La impactul de 20 J, structurile cu TPU-STF au redus forța maximă de la 8,32 kN pentru GFRP simplu la 6,87 kN pentru STF-20 și 6,89 kN pentru STF-25, adică o reducere de aproximativ 17%. Observațiile post-impact au confirmat diferența structurală dintre probe. Laminatul GFRP simplu a prezentat perforare locală, în timp ce probele cu inserție TPU-STF nu au fost perforate pe fața inferioară. Acest rezultat arată că deformarea mai mare a probelor cu STF nu reprezintă o cedare prin străpungere, ci un răspuns controlat, prin care energia impactului este distribuită pe o durată mai mare și pe o zonă mai extinsă.

Probele testate la 60 J au evidențiat forțe maxime de aproximativ 9,6-10,0 kN pentru probele cu STF, menținând un răspuns controlat prin deformare. Aceste rezultate susțin ideea că inserția TPU-STF poate contribui la limitarea deteriorării locale și la obținerea unei protecții la impact cu adaos redus de material. Prin urmare, soluția propusă poate reprezenta o alternativă mai ușoară față de creșterea grosimii laminatului prin adăugarea de straturi suplimentare de fibră de sticlă.

Cercetările viitoare pot viza analiza comportamentului la vibrații, influența temperaturii asupra vâscozității și stabilității STF-ului, testarea la impact repetat, studiul comportamentului în timp al lichidului încapsulat și optimizarea aderenței dintre TPU și rășina epoxidică. De asemenea, pot fi investigate geometrii diferite ale capsulei, grosimi variabile ale filmului TPU și modele numerice pentru analiza distribuției tensiunilor în zona de impact.

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8. Notății

Următoarele simboluri sunt utilizate în cadrul lucrării:

$F_{max,GFRP}$ = forța maximă medie pentru laminatul GFRP simplu [kN];

$F_{max,STF}$ = forța maximă medie pentru structura GFRP/TPU-STF [kN]; m =

masa impactorului [kg]; m_{PEG400} = masa de PEG400 utilizată la prepararea

STF-ului [g]; m_{SiO_2} = masa de dioxid de siliciu utilizată la prepararea STF-

ului [g]; RF = reducerea procentuală a forței maxime [%]; $t_{contact}$ = durata

de contact dintre impactor și probă [ms]; t_{Fmax} = timpul la care se atinge

forța maximă [ms]; v = viteza impactorului [m/s];

w_{SiO_2} = concentrația masică de dioxid de siliciu în STF [%];

GFRP = material compozit ranforsat cu fibră de sticlă, Glass Fiber Reinforced Polymer;

PEG400 = polietilenglicol 400;

SiO_2 = dioxid de siliciu;

STF = lichid cu îngroșare la forfecare, Shear-Thickening Fluid;

TPU = poliuretan termoplastic, Thermoplastic Polyurethane; wt.%

= procent masic; rpm = rotații pe minut.

PARAMETRIC STUDY OF AUXETIC STRUCTURES LOADED IN COMPRESSION

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REZUMAT:

This paper presents a parametric study on two-dimensional reentrant hexagonal auxetic structures. The study is based on structures loaded in compression. The static loading has been modelled using Ansys 2025.

The influence of various design parameters has been highlighted when it comes to the effect on the Poisson ratio and on the stress distribution in the part.

CUVINTE CHEIE: auxetice, coeficient Poisson

Introducere

Materialele și structurile auxetice prezintă un coeficient Poisson negativ, ceea ce înseamnă că se extind transversal când sunt solicitate la tensiune și se contractă transversal când sunt solicitate la compresie. În cadrul acestei lucrări, s-a realizat un studiu parametric pentru o structură auxetică bidimensională, folosind analiza cu elemente finite în programul Ansys 2025.

Obiectivele studiului sunt:

- Proiectarea unei structuri auxetice bidimensionale parametrizate.
- Identificarea influenței diversilor parametri asupra coeficientului Poisson.
- Identificarea influenței diversilor parametri asupra solicitărilor din structură.

Stadiul actual

Numărul lucrărilor de cercetare care privesc materialele auxetice a crescut exponențial de la introducerea lor în 1987 de către Lakes Invalid source specified..

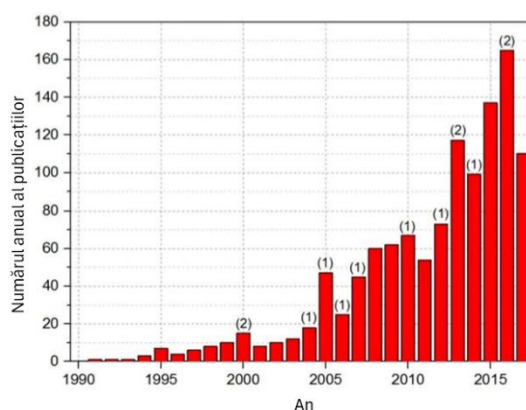


Fig. 20. Numărul de publicații despre materiale auxetice în perioada 1991-2008 (în paranteză sunt lucrările de tip review) Invalid source specified.

Printre proprietățile deosebite ale auxeticilor se remarcă răspunsul îmbunătățit la sarcinile de impact. Sub acțiunea unei sarcini de impact localizate, un material convențional cu un coeficient Poisson pozitiv este comprimat în direcția sarcinii și se extinde în toate direcțiile perpendiculare acesteia. În schimb, un material auxetic se va contracta în direcția impactului, crescând densitatea locală a materialului. Acest fenomen permite materialului auxetic să absoarbă o parte din energia generată de

impact, oferind astfel o rezistență mai eficientă la impact. Aceasta reprezintă baza aplicațiilor sale în domeniul absorbției vibrațiilor și șocurilor, așa cum este ilustrat în Fig. 21.

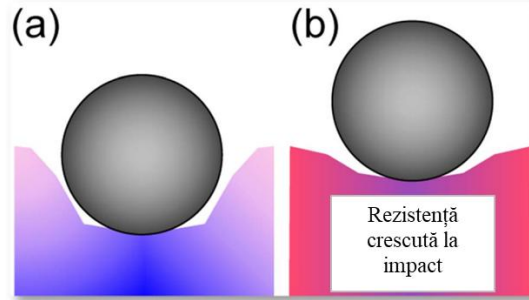


Fig. 21. Comportamentul materialelor non-auxetice (a) și auxetice (b) sub sarcină localizatăInvalid source specified.

Astfel, materialele auxetice au aplicații atât în ingineria civilă, cât și în structuri de impact și armuri. Deoarece coeficientul Poisson negativ este cel care determină răspunsul lor sub solicitarea de compresiune, lucrarea de față se axează pe determinarea unui coeficient cât mai mic.

Definirea modelului de bază pentru studiul parametric

Structura a fost realizată în modulul Ansys Design Modeler, pe baza unei celule multiplicate. Structura este construită în plan, din suprafețe.

Parametrii folosiți în definirea modelului se pot observa în Fig. 22 și în Tabelul 1.

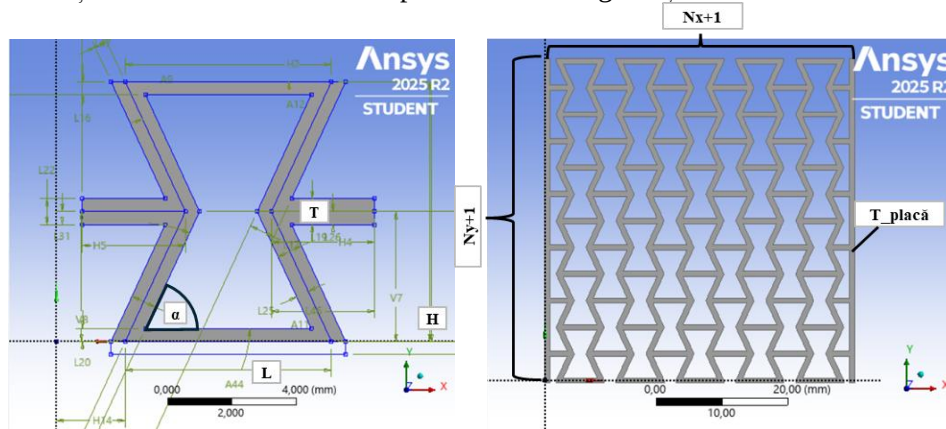


Fig. 22. Parametrii folosiți pentru structura bidimensională

Tabelul 1. Parametrii folosiți pentru structura bidimensională

Parametru	Reprezintă	Valoare de bază	Interval de valori
T	Grosimea	0,8mm	0,4...1,2mm
α	Unghiul	65°	58...75°
L	Lățimea	6,4mm	7...12mm
H	Înălțimea	8mm	6...12mm
Nx+1	Numărul de celule în direcția x	4+1	1+1...8+1
Ny+1	Numărul de celule în direcția y	5+1	1+1...8+1
T_placă	Grosimea plăcii, =T	0,8mm	0,4...1,2mm

În calcule, s-a considerat o grosime a structurii de 10mm.

Dimensiunile de gabarit ale modelului sunt:

$$\text{- În direcția X: } \left(2L - \frac{H}{\tan \alpha} \right) \cdot (Nx + 1) + 2T_{\text{placă}} \quad (1)$$

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$$- \text{În direcția } Y: H \cdot (N_y + 1) + T \quad (2)$$

Pentru modelul de bază, acestea sunt egale cu 46,95mm, respectiv 48,8mm.

Materialul folosit în analiză a fost ales pentru a fi similar cu un posibil material de fabricație (PLA). Acesta are următoarele caracteristici:

- Densitate de 1250 kg/m³
- Modul de elasticitate Young de 3,45GPa
- Coeficient Poisson de 0,39
- Limita de curgere de 54,1MPa
- Limita de rupere de 59,2MPa

Pentru încărcarea structurii, s-a aplicat o forță de 100N în direcția x. Latura opusă a fost încastrată. Această condiție la limită poate influența rezultatele.

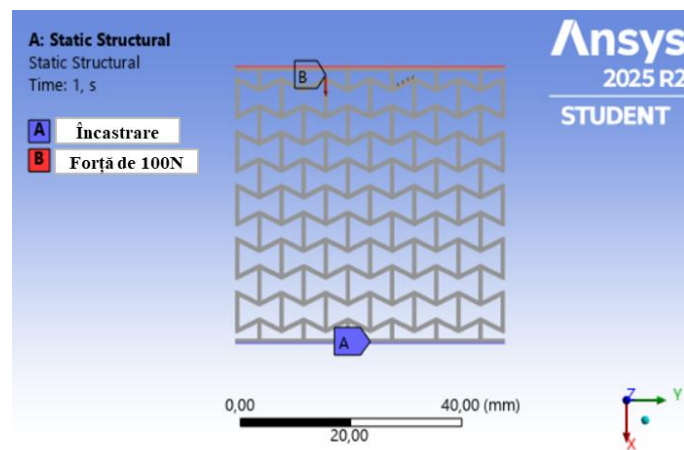


Fig. 23. Aplicarea încărcărilor și a condițiilor la limită

Analiza rulată este de tip static, neliniar (activând opțiunea deformărilor mari). S-au urmărit două tipuri de rezultate:

- Deformațiile structurii (pentru calculul coeficientului Poisson)
- Solicitățile de compresiune și tensiune principale din material

Solicitățile principale au fost extrase direct din program.

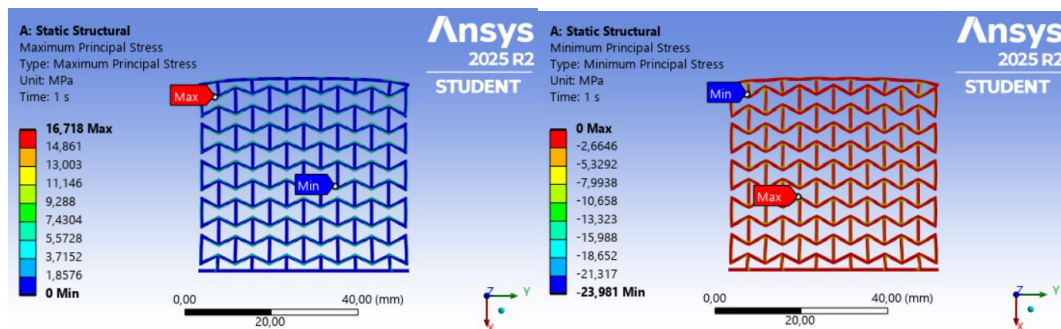


Fig. 24. Solicitățile maximă și minimă principală obținută pentru modelul de bază

Ecuatiile folosite la calculul coeficientului Poisson sunt:

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$$\varepsilon_x = \frac{\Delta x}{\left(2L - \frac{H}{\tan \alpha}\right) \cdot (Nx+1) + 2T_{placă}} [-] \quad (3)$$

Δx este deplasarea măsurată la mijlocul laturii de aplicare a încărcării [mm] (4)

$$\varepsilon_y = \frac{\Delta y}{H \cdot (Ny+1) + T} [-] \quad (5)$$

Δy este diferența dintre deplasările maximă și minimă pe direcția y [mm] (6)

$$\nu = \frac{-\varepsilon_y}{\varepsilon_x} [mm] \quad (6)$$

Trebuie menționat că determinarea coeficientului Poisson este realizată pentru condițiile la limită ale structurii descrise mai sus. Astfel, valorile obținute pot să fie mai mici decât -1.

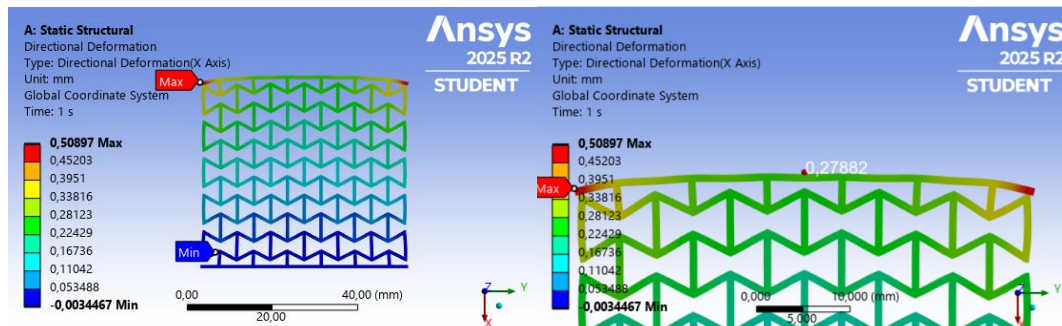


Fig. 25. Deformată în direcția încărcării în modelul de bază

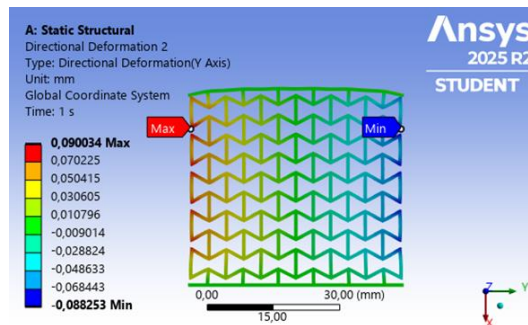


Fig. 26. Deformată în direcție transversală în modelul de bază

Rezultatele pentru modelul de bază sunt prezentate în Tabelul 2.

Tabelul 2. Rezultate pentru modelul de bază

Model	Coeficientul Poisson	Solicitarea maximă principală [MPa]	Solicitarea maximă principală [MPa]
Model de bază	-0,615	16,718	-23,981

A fost realizat un studiu de convergență pentru discretizare. S-au folosit dimensiuni ale elementelor cuprinse între limita inferioară (cauzată de limitarea numărului de noduri din licența Ansys Student) și valoarea grosimii T. Concluzia studiului de convergență este că o discretizare cu dimensiunea cuprinsă între T/4 și T/3 este suficientă pentru model. Decizia a fost luată în funcție de valorile medii, care se situează între rezultatele evidențiate cu albastru în Tabelul 3.

PARAMETRIC STUDY OF AUXETIC STRUCTURES

LOADED IN COMPRESSION

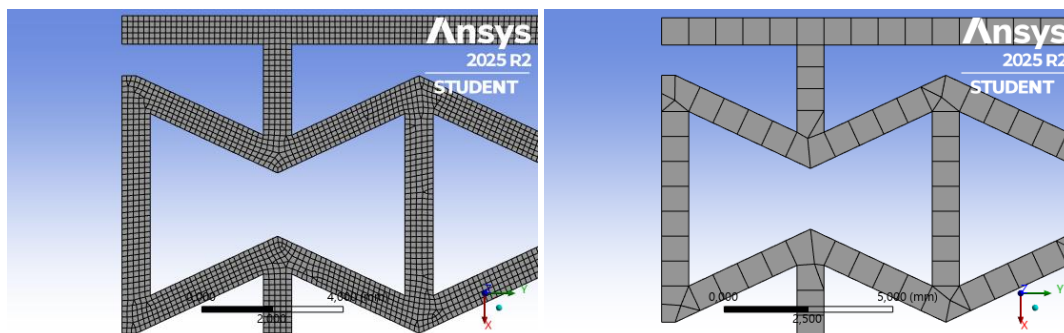


Fig. 27. Aspectul discretizărilor de 0,1545mm și 0,8mm

Tabelul 3. Rezultate pentru studiul de convergență

Dimensiunea discretizării [mm]	Coeficientul Poisson	Solicitarea maximă principală [MPa]	Solicitarea maximă principală [MPa]	Timpe de rulare a analizei [s]
Minimă, 0,1545	-0,6162	16,759	-27,403	3,172
T/5 = 0,16	-0,6157	16,773	-26,725	3,047
T/4 = 0,2	-0,6152	16,718	-23,981	3,328
0,24	-0,6149	16,724	-22,049	3,328
Aprox. T/3 = 0,35	-0,6131	16,646	-18,584	1,359
T/2 = 0,4	-0,6105	16,209	-16,437	0,828
T/1 = 0,8	-0,6083	16,38	-12,139	0,688
Valoare medie	-0,6134	16,601	-21,045	

Studiu parametric

Influența grosimii

S-au studiat structuri cu grosimea cuprinsă între 0,4mm și 1,2mm. S-a folosit aceeași grosime și pentru placă.

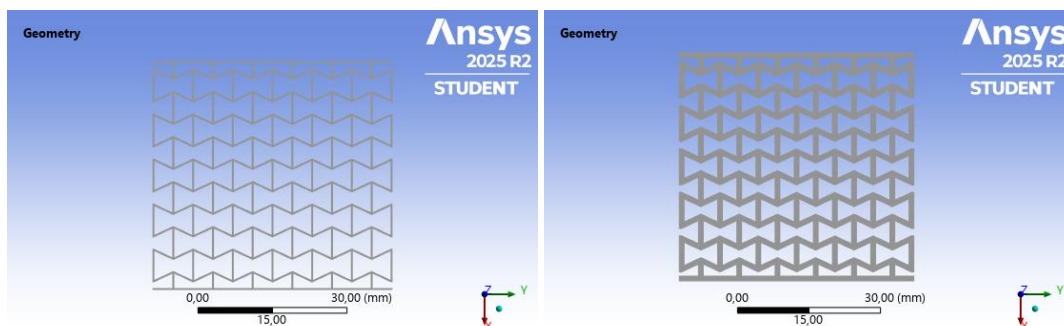


Fig. 28. Aspectul grosimilor de 0,4mm și 1,2mm

Tabelul 4. Rezultate pentru studiul grosimii

Grosime [mm]	Coeficientul Poisson	Solicitarea maximă principală [MPa]	Solicitarea maximă principală [MPa]
0,4	-0,816	77,8	-97,9
0,6	-0,691	31,8	-43,2
0,8	-0,615	16,7	-24,0
1	-0,545	10,1	-16,6
1,2	-0,476	6,5	-12,5

PARAMETRIC STUDY OF AUXETIC STRUCTURES

LOADED IN COMPRESSION

Influența unghiului

S-au studiat structuri cu unghiul cuprins între 58° și 75° .

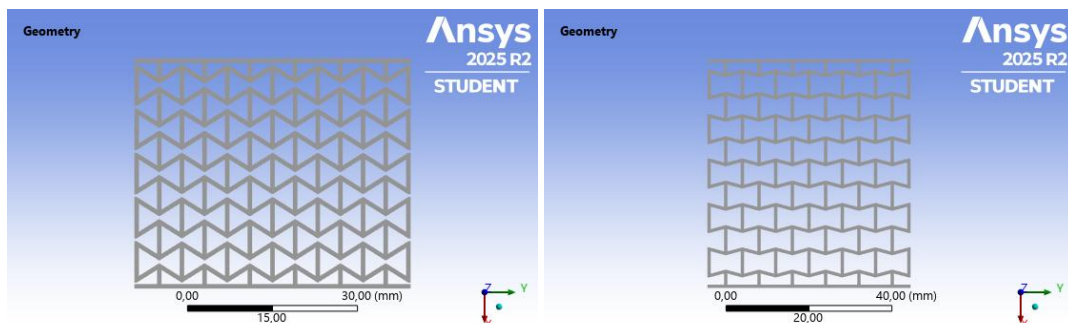


Fig. 29. Aspectul unghiurilor de 58° și 75°

Unghi [$^\circ$]	Coeficientul Poisson	Solicitarea maximă principală [MPa]	Solicitarea maximă principală [MPa]
58	-0,766	16,8	-23,8
60	-0,725	16,7	-24,4
65	-0,615	16,7	-24,0
70	-0,501	16,4	-23,4
75	-0,387	15,9	-24,2

Tabelul 5. Rezultate pentru studiul unghiului

Influența numărului de celule

S-au studiat structuri cu N_x , N_y cuprinse între 1 și 8. Pentru studiul N_x , dimensiunea discretizării a fost modificată la 0,24mm, astfel încât toate modelele să aibă aceeași grilă ca modelul cel mai mare ($N_x=8$).

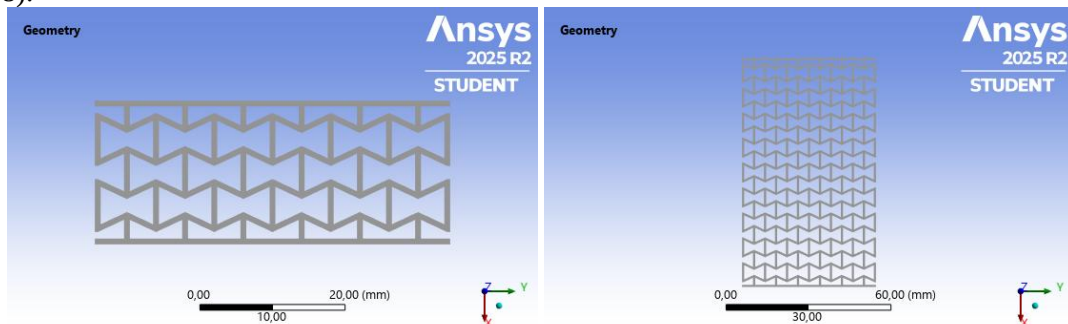


Fig. 30. Aspectul modelelor cu $N_x=1$ și $N_x=8$, pentru $N_y=5$

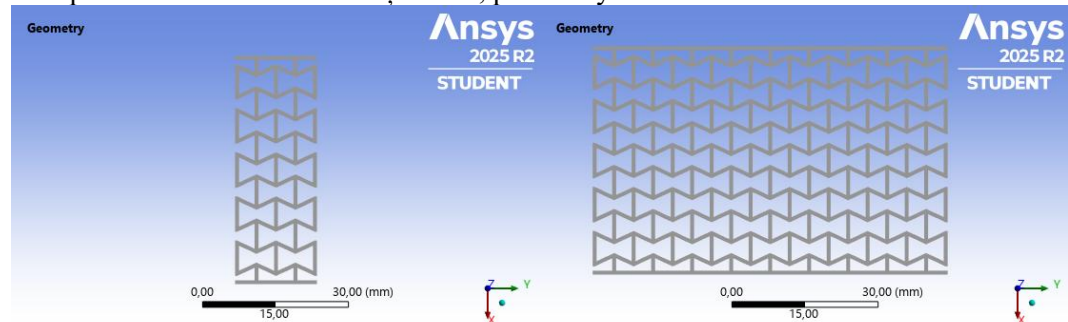


Fig. 31. Aspectul modelelor cu $N_y=1$ și $N_x=8$, pentru $N_x=4$

PARAMETRIC STUDY OF AUXETIC STRUCTURES

LOADED IN COMPRESSION

Tabelul 6. Rezultate pentru studiul numărului de celule

N_x [-]	N_y [-]	Coeficientul Poisson	Solicitarea maximă principală [MPa]	Solicitarea maximă principală [MPa]
1	5	-0,739	16,95	-23,98
2	5	-0,679	16,78	-22,18
3	5	-0,639	16,74	-22,08
4	5	-0,615	16,72	-22,05
5	5	-0,599	16,72	-22,04
6	5	-0,588	16,72	-22,04
7	5	-0,576	16,72	-22,04
8	5	-0,573	16,72	-22,04
4	1	-0,584	44,7	-66,0
4	2	-0,624	29,9	-45,1
4	3	-0,610	23,7	-33,9
4	4	-0,643	19,6	-27,9
4	5	-0,615	16,7	-24,0
4	6	-0,643	14,5	-21,0
4	7	-0,604	12,8	-18,6
4	8	-0,629	11,4	-16,7

Influența raportului dintre lățime și înălțime

Prin variația dimensiunii L, s-a modificat raportul L/H. Au fost studiate rapoarte L/H cuprinse între 0,7 și 1,2.

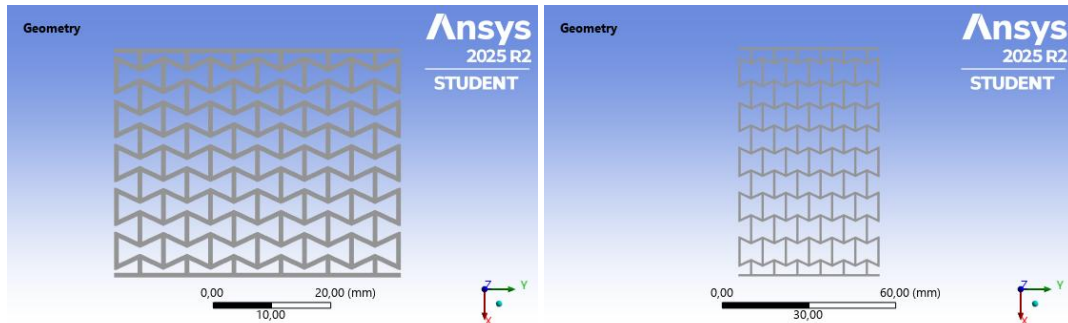


Fig. 32. Aspectul rapoartelor L/H de 0,7 și 1,2

Tabelul 7. Rezultate pentru studiul raportului L/H

L/H [-]	Coeficientul Poisson	Solicitarea maximă principală [MPa]	Solicitarea maximă principală [MPa]
0,7	-0,528	16,7	-24,3
0,8	-0,615	16,7	-24,0
0,9	-0,700	16,7	-23,7
1	-0,780	16,6	-23,3
1,2	-0,934	16,4	-23,0

Concluzii

Concluziile studiului parametric sunt sumarizate în Tabelul 8.

Tabelul 8. Influența parametrilor asupra coeficientului Poisson și asupra solicitărilor		
Parametru	Pentru scăderea coeficientului Poisson	Pentru scăderea solicitărilor
Grosime	Scăderea grosimii	Creșterea grosimii
Unghi	Scăderea unghiului	
Numărul de celule Nx	Scăderea Nx	
Numărul de celule Ny		Creșterea Ny
Raportul L/H	Creșterea raportului	

Lucrarea de față constituie baza unui studiu avansat privind crearea unor structuri auxetice cu proprietăți optimizate pentru aplicații specifice. Înțelegerea influenței fiecărui parametru este punctul de plecare pentru proiectarea diverselor corpuri cu răspuns îmbunătățit la solicitări de compresie sau de impact.

Studiul va continua prin validarea experimentală a rezultatelor. Plecând de la concluziile expuse în Tabelul 8, se va realiza proiectarea unei structuri cu un coeficient Poisson mult mai mic decât cel al modelului de bază. Ambele specimene vor fi printate 3D, folosind materiale asemănătoare cu cel definit în cadrul analizei cu elemente finite.

Printre îmbunătățirile posibile ale studiului se numără includerea mai multor tipuri de geometrii și materiale. De asemenea, pe lângă răspunsul static la solicitări de compresie, poate fi analizat și răspunsul dinamic în caz de impact.

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Notații

Următoarele simboluri sunt utilizate în cadrul lucrării:

H = Înălțimea celulei [mm];

L = Lățimea celulei [mm];

N_x, N_y = Numărul de unități dintr-o anumită direcție [-];

PLA = Acid polilactic;

T = Grosimea celulei [mm];

$T_{\text{placă}}$ = Grosimea plăcii de introducere a solicitării [mm];

α = Unghiul celulei [°];

ϵ_x = Deformația longitudinală a structurii [-];

ϵ_y = Deformația transversală a structurii [-];

ν = Coeficient Poisson [-]

AUTOMATED PACKAGE SORTING SYSTEM BASED ON COLOR DETECTION

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***ABSTRACT:** This paper presents a small-scale automated package sorting system based on color detection. The prototype uses a 3D-printed conveyor driven by a 12 V DC motor through an L298N driver, a TCS3200 RGB color sensor, an SG90 servomotor and an Arduino UNO controller. Red and green packages are deviated toward lateral collection areas, while blue packages continue to the end of the belt. The prototype reproduces the main stages of an industrial sorting line: transport, detection, decision and mechanical actuation.*

***KEY WORDS:** automated sorting, conveyor, color sensor, Arduino.*

1. Introduction

Automated handling systems are increasingly used in applications where objects must be moved, identified and separated with minimal human intervention. By replacing repetitive manual operations, such systems can improve consistency, reduce sorting errors and make the overall workflow easier to control.

In this paper, color is treated as a simple visual characteristic that can be used to distinguish between different packages. The purpose is not only to separate objects according to their color, but also to demonstrate how mechanical movement, electronic sensing and software control can work together in a compact mechatronic system.

The project focuses on the development of a functional prototype in which the conveyor moves the packages through the sensing area, the color sensor provides the information needed for classification, and the actuator changes the path of the package according to the detected result. The main objectives were to design a modular mechanical structure with 3D-printed components, to connect the sensing and actuation elements to the Arduino-based control unit, to implement the sorting logic in software and to test the operation of the system for three color categories: red, green and blue.

2. Current state and applicability of the project

Color-based sorting is used in logistics, recycling, packaging and quality control. Systems developed by Beumer Group [11], Vanderlande [12], Honeywell or Siemens Logistics operate at high throughput rates, but they follow the same general principle: identifying the object and diverting it to the correct destination.

Industrial sorters may be of the cross-belt, tilt-tray or pusher type. The prototype uses a simplified pusher version: the package is detected, the color is established, and a paddle actuated by a servomotor diverts it.

In industry, cameras, hyperspectral sensors or dedicated color sensors are used. For educational applications, the TCS3200 [8] is suitable because it converts the intensity of reflected light into frequency and allows color differentiation under controlled conditions.

The cited works [1], [2], [3], [4] confirm that the Arduino-TCS3200 architecture can perform the sorting of colored objects in laboratory applications, with response times compatible with reduced belt speeds.

The specific elements of the project are three-color sorting, software control of the motor through the L298N, the modular structure with 3D-printed parts and the separate power supply of the motor from

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the logic circuits.

The system can be related to applications in distribution, recycling, the food industry and the pharmaceutical industry, where objects are separated by color, batch, destination or material type.

3. Description of the proposed system

The sorting system is a small-scale implementation of a complete mechatronic chain, consisting of three levels: mechanical, electronic and software.

The mechanical level ensures the movement of packages on the belt and the positioning of the guiding elements. The structure made of T-slot profiles and 3D-printed parts allows fast assembly and reconfiguration.

The electronic level includes the Arduino UNO [7], the TCS3200 sensor [8], the L298N driver [10], the SG90 servomotor [9] and the separate power supplies for the logic side and the power side, with a common reference ground. The software level performs the read-decision-actuation cycle: it reads the RGB frequencies, compares the obtained values, establishes the dominant color, commands the paddle and maintains the belt speed through PWM.

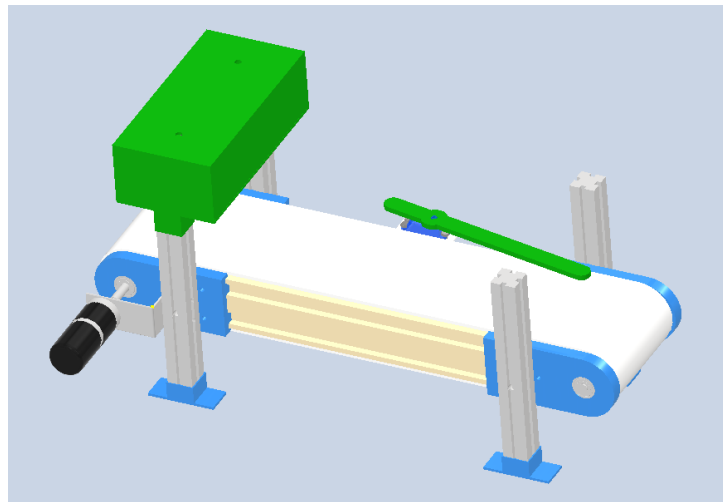


Fig. 1. The virtual model of the system

Table 1. Correspondence between physical components, code and functionality

Physical component	Code element	Function in the system
TCS3200 sensor	pulseIn() on OUT pin	Returns R, G, B frequencies
S2, S3 pins of TCS3200	digitalWrite(S2, S3, ...)	Selects the active color filter
SG90 servomotor	servo.write(angle)	Positions the deviation paddle
12 V DC motor	analogWrite(ENA)	Belt motion with software-adjustable speed
L298N driver	digitalWrite(IN1, IN2)	Control of DC motor direction and speed

The division into levels reflects the classical architecture of a mechatronic system [6]: the mechanics performs the motion, the electronics receives the signals and transmits the commands, and the software transforms the measurements into actions.

3.1. Mechanical components

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The frame is made of T-slot profiles and 3D-printed supports. The belt is driven by a roller with a diameter of 63 mm, with a useful length of approximately 450 mm and a width of 200 mm. The TCS3200 sensor is mounted at the conveyor inlet, while the SG90 paddle is positioned after the reading area in order to divert the package after identification.

The motor sizing was carried out starting from the traction force, the torque required at the shaft and the mechanical power required for belt movement.

The linear speed selected for the belt is $v = 8 \text{ cm/s} = 0.08 \text{ m/s}$, low enough for the sensor to read the color steadily and for the servomotor to actuate before the object passes the paddle.

For the drive roller with $D = 63 \text{ mm}$ and $r = 0.0315 \text{ m}$, the speed required at the reducer output is determined from the relationship between linear speed and angular speed:

$$n = \frac{v}{2\pi r} \cdot 60 = \frac{0,08}{2\pi \cdot 0,0315} \cdot 60 \approx 24,3 \text{ rot/min} \quad (1)$$

The traction force depends on the total transported weight and on the friction coefficient.

The calculation considered the mass of the package and the mass of the useful belt section:

$$m_{\text{banda}} = 0,450 \cdot 0,200 \cdot 0,0015 \cdot 1400 \approx 0,19 \text{ kg} \quad (2)$$

For the PVC belt on a 3D-printed surface, a friction coefficient of $\mu = 0.3$ was adopted. The total equivalent weight is:

$$G_{\text{total}} = (m_{\text{colet}} + m_{\text{banda}}) \cdot g = (0,2 + 0,19) \cdot 9,81 \approx 3,83 \text{ N} \quad (3)$$

The resulting traction force is:

$$F = G_{\text{total}} \cdot \mu = 3,83 \cdot 0,3 \approx 1,15 \text{ N} \quad (4)$$

The torque required at the shaft is obtained from the product of the traction force and the roller radius:

$$M = F \cdot r = 1,15 \cdot 0,0315 \approx 0,036 \text{ Nm} \quad (5)$$

The mechanical power is calculated using the relationship:

$$P = F \cdot v = 1,15 \cdot 0,08 \approx 0,092 \text{ W} \quad (6)$$

Considering the transmission efficiency $\eta = 0.75$, the required electrical power becomes:

$$P_{\text{elec}} = \frac{P}{\eta} = \frac{0,092}{0,75} \approx 0,123 \text{ W} \quad (7)$$

The obtained result is below 0.15 W, therefore a low-power DC motor is sufficient for this application. Since the roller must operate at approximately 24 rpm, while simple DC motors have much higher speeds, a reduction ratio is required:

$$i = \frac{n_{\text{motor}}}{n_{\text{rolă}}} = \frac{3000}{24,3} \approx 123 \Rightarrow i = 150 \div 300:1 \quad (8)$$

The DC motor with integrated reducer provides speed reduction and torque increase without

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additional external mechanisms, which simplifies the assembly of the prototype. The moment of inertia of the load referred to the motor shaft was also checked. The roller was considered as a solid PLA cylinder:

$$J_{rol\breve{a}} = \frac{1}{2} \cdot m_{rol\breve{a}} \cdot r^2 \quad (9)$$

Roller mass:

$$m_{rol\breve{a}} = \rho \cdot \pi \cdot r^2 \cdot L = 1250 \cdot \pi \cdot 0,0315^2 \cdot 0,2 \approx 0,78 \text{ kg} \quad (10)$$

Moment of inertia of the roller:

$$J_{rol\breve{a}} = \frac{1}{2} \cdot 0,78 \cdot 0,0315^2 \approx 3,87 \times 10^{-4} \text{ kg} \cdot \text{m}^2 \quad (11)$$

Equivalent moment of inertia of the package and the belt:

$$J_{rol\breve{a}} = \frac{1}{2} \cdot 0,78 \cdot 0,0315^2 \approx 3,87 \times 10^{-4} \text{ kg} \cdot \text{m}^2 \quad (12)$$

Total moment of inertia:

$$J_{total} = J_{rol\breve{a}} + J_{sarcin\breve{a}} \approx 7,74 \times 10^{-4} \text{ kg} \cdot \text{m}^2 \quad (13)$$

The reduced value confirms that the selected motor can accelerate and keep the belt moving without exceeding the torque limits.

The selected motor is a 12 V DC motor with integrated reducer, 20-30 rpm, a 150-300:1 ratio and a minimum torque of 0.1 Nm, above the calculated torque.

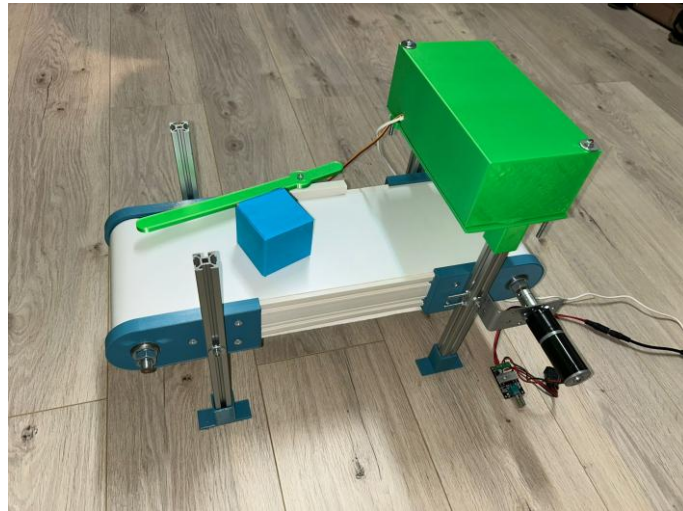


Fig. 2. Overview of the sorting system

3.2. Electronic components

Arduino UNO centralizes the signals. TCS3200 transmits the measured frequency through the OUT pin, and SG90 receives the position command on D9.

The motor is controlled through L298N: ENA regulates the speed through PWM, and

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IN1/IN2 establish the direction of rotation. The motor is powered separately at 12 V, while Arduino, the sensor and the servomotor use the logic power supply. The common ground preserves the reference, and the separation reduces disturbances.

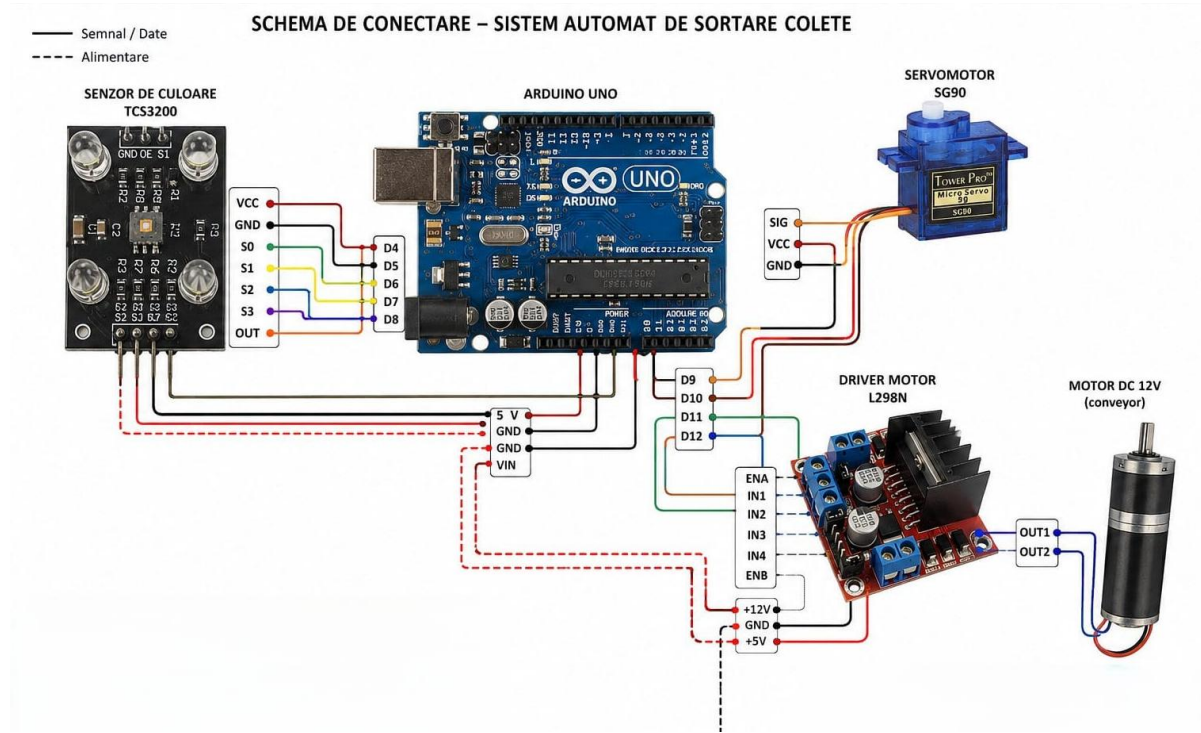


Fig. 3. Connection diagram of the automated sorting system

4. System operation and software implementation

The Arduino [5] program establishes the connections for the TCS3200 sensor, the SG90 servomotor and the L298N driver, then repeatedly executes the cycle: color reading, comparison of RGB values and paddle positioning. The belt motor is started through the L298N driver, and the speed is adjusted by a PWM signal. The sorting decision is based on comparing the three measured durations. The channel with the minimum duration corresponds to the highest frequency and is considered the dominant color of the package.

$$f_R > f_G \text{ și } f_R > f_B \rightarrow \text{red} \quad (14)$$

$$f_G > f_R \text{ și } f_G > f_B \rightarrow \text{green} \quad (15)$$

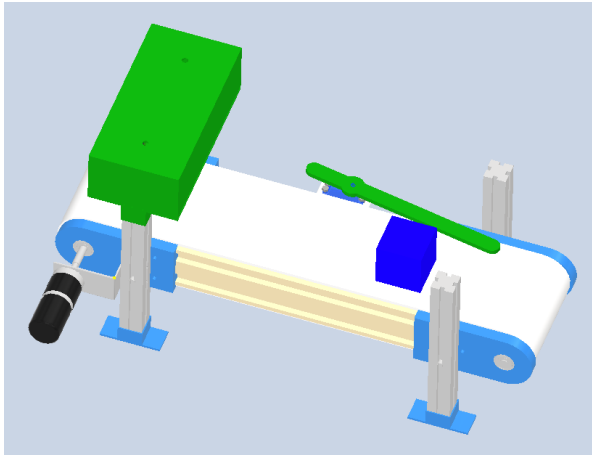
$$f_B > f_R \text{ și } f_B > f_G \rightarrow \text{blue} \quad (16)$$

The thresholds were established experimentally. The dominant color has a pulse of approximately 0.8-0.9 ms, while the other channels have 2.0-2.4 ms; calibration depends on lighting and distance. After identifying the color, Arduino commands the SG90 servomotor to the position associated with the detected category. The paddle diverts the package for red and green, while for blue it remains in the rest position.

For blue packages, the paddle is not activated. The package continues moving to the end of the belt,

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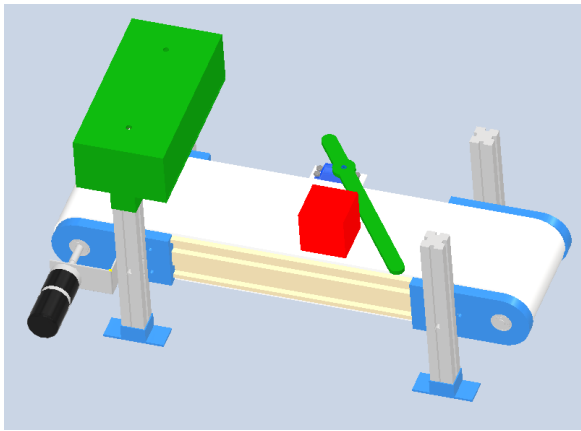
this option being considered the default route of the system.



```
// =====  
void loop()  
{  
  readColor();  
  
  Serial.print("R = ");  
  Serial.print(redFrequency);  
  
  Serial.print(" G = ");  
  Serial.print(greenFrequency);  
  
  Serial.print(" B = ");  
  Serial.println(blueFrequency);  
  
  // =====  
  // ALBASTRU  
  // =====  
  if (blueFrequency < redFrequency &&  
      blueFrequency < greenFrequency)  
  {  
    Serial.println("ALBASTRU");  
  
    sorter.write(pozitieInitiala);  
  
    delay(100);  
  }  
}
```

Fig. 4. Code sequence for the color blue

For red packages, Arduino commands the `servo.write(60)` position. The paddle maintains the position long enough for the package to be evacuated, then returns to 90° .

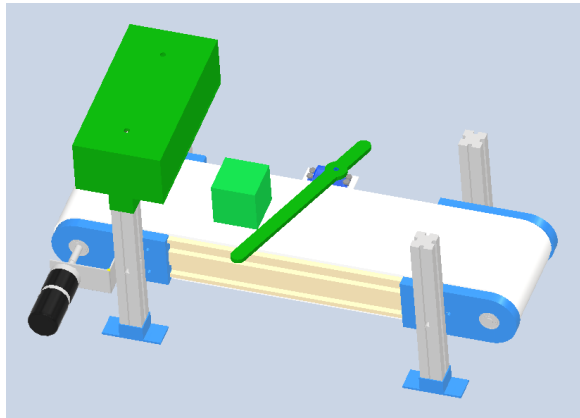


```
// =====  
// ROSU  
// =====  
else if (redFrequency < blueFrequency &&  
        redFrequency < greenFrequency)  
{  
  Serial.println("ROSU");  
  
  sorter.write(pozitieRosu);  
  
  delay(timpRevenire);  
  
  sorter.write(pozitieInitiala);  
  
  delay(500);  
}
```

Fig. 5. Code sequence for the color red

For green packages, the paddle is positioned at approximately 20° through `servo.write(20)`, obtaining a different deviation compared with red packages. After sorting, the paddle returns to the initial position

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```
// =====  
// VERDE  
// =====  
else if (greenFrequency < redFrequency &&  
        greenFrequency < blueFrequency)  
{  
    Serial.println("VERDE");  
    sorter.write(pozitieVerde);  
    delay(timpRevenire);  
    sorter.write(pozitieInitiala);  
    delay(500);  
}  
delay(50);  
}
```

Fig. 6. Code sequence for the color green

5. Experimental results

To evaluate the system, tests were performed under three lighting conditions: artificial white light, artificial yellow light and ambient lighting. Red, green and blue packages were analyzed. The RGB values supplied by TCS3200 and the percentage of correct identifications were monitored in order to determine the influence of lighting on accuracy.

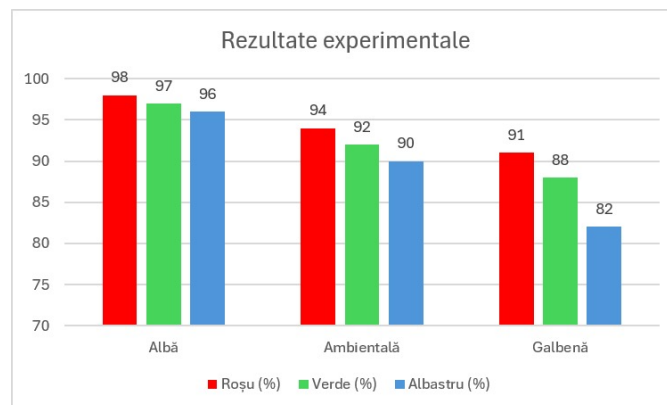


Fig. 7. Influence of lighting conditions on color identification accuracy

For each color, 20 tests were performed: 20/20 red, 18/20 green and 19/20 blue, resulting in an average success rate of 95%.

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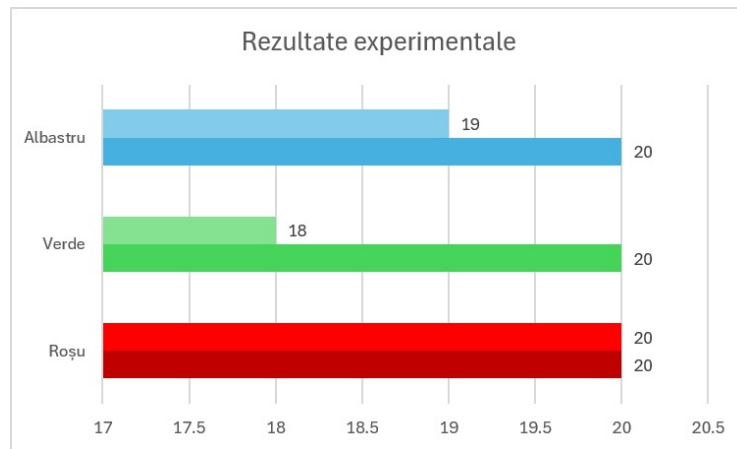


Fig. 8. Sorting success rate for each package category

The results confirm the operation of the algorithm and of the sorting mechanism, with 100% success for red, 90% for green and 95% for blue. The results show that L298N maintains the belt speed, while SG90 positions the paddle repeatedly. The remaining errors mainly occur due to lighting and package positioning. The errors were mainly caused by lighting variations, the positioning of the package relative to the sensor and differences in the reflection of the analyzed surfaces

Table 2. Synthetic results of prototype testing

Parameter	Measured value
Tests performed	60 tests (20/color)
Sorting success rate	95% (57/60)
Color identification time	180 ms
Paddle active time	3000 ms

6. Conclusions

The prototype confirmed that automatic package sorting based on color can be achieved using a simple mechatronic system. The conveyor, TCS3200 sensor, Arduino UNO board, L298N driver and SG90 servomotor worked together to identify and separate red, green and blue packages. The tests showed an overall success rate of 95%, proving that the system is functional for small-scale sorting applications. The main limitations were caused by lighting conditions, package positioning and surface reflections. In conclusion, the project achieved its objective and demonstrated the practical connection between mechanical design, electronics and software control. Future improvements may include additional colors, HSV-based detection, an LCD display, Wi-Fi monitoring or a camera-based recognition system.

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8. Notations

fR, fG, fB = output frequencies of the TCS3200 sensor for the red, green and blue filters [Hz];
PWM = pulse width modulation;
RGB = red-green-blue color model;
HSV = hue-saturation-value color model

DEVELOPMENT OF AN AUTOMATIC PRODUCT IDENTIFICATION AND MANAGEMENT SYSTEM USING RFID TECHNOLOGY

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***ABSTRACT:** This project presents an automatic product identification and management system that uses RFID technology integrated an Excel interface built using Visual Basics for Applications. The connection between the data received from the RFID tags and the visual interface is made by a Python application that reads the UIDs from the tags and looks them up in the Excel database. The hardware module of the projects is built around an Arduino Mega 2560 and a MFRC522 RFID reader, the other component being: an I2C LCD display that shows messages for the user and a piezo buzzer that gives different alerts, all inside a custom case designed in Autodesk Inventor and 3D-printed. The system was tested with a small database and showed the features of a low-cost alternative for an automatic product identification and management system that can be implemented in retail.*

***KEYWORDS:** RFID, identification, Arduino, Excel.*

1. Introduction

In the current context of accelerated digitalization and automation of commerce, automatic product identification and monitoring has become an essential component for retail companies present on the market. Barcode-based technologies are still widely used today, but RFID technology, which appeared in retail in the early 2000s, offers new advantages over its predecessor: the possibility of reading a tag without direct line of sight, resistance to mechanical wear, and the ability to read multiple products simultaneously.

This paper presents the design and implementation of a small-scale automatic system that uses RFID technology to manage products from a database representing a clothing store. The main objectives achieved through this project are: (1) building a hardware device consisting of a case designed in Autodesk Inventor that protects and houses all the other hardware components of the project, (2) implementing a software application that connects an Arduino board, a Python application and an interactive Excel interface, and (3) automating and monitoring the process of scanning various RFID tags, calculating the final total and generating a PDF receipt for the user.

All three objectives of the paper were achieved as follows: (1) the hardware device was assembled and contains an Arduino Mega 2560 board, an MFRC522 RFID reader, an I2C LCD display and a buzzer, (2) the application was implemented and runs in Python, performing the following actions: identifying the scanned product in the database, updating the shopping cart, checking the current stock and generating the PDF receipt, and (3) the application was created in Excel using VBA macros and functions both as a product database and as a user interface. The proposed solution demonstrates that a combination of low-cost hardware and commonly available software tools can provide a functional, accessible and scalable RFID-based product management system.

2. Current state

Currently, automatic product identification and management systems are usually composed of barcode readers, payment terminals and management applications. The use of RFID technology, although not new, is on an upward trend that has emerged alongside the reduction in the cost of passive tags [2]. Many of the major retail chains already use this technology for easier inventory management and a faster checkout process. The advantages of using this technology are undeniable and include: the ability to read multiple products simultaneously without the need to scan each one

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individually, and real-time inventory of the current stock [10].

Existing RFID-based solutions are usually implemented in complex commercial systems, which include dedicated databases, specialized software applications and industrial equipment. By comparison, this paper proposes the development of a low-cost prototype, using accessible components such as Arduino, an RFID reader, an Excel interface and a Python program, to demonstrate the operating principle of an automatic product identification and management system.

3. System architecture

The proposed system is structured into three functional levels: the hardware level, the processing level (the Python application) and the database and interface level (the Excel file with VBA macros). Communication between the three components is carried out as follows: the Arduino communicates with the PC via the USB serial port, while the Python application interacts with Excel through the xlwings library, which allows real-time control of an open workbook [3].

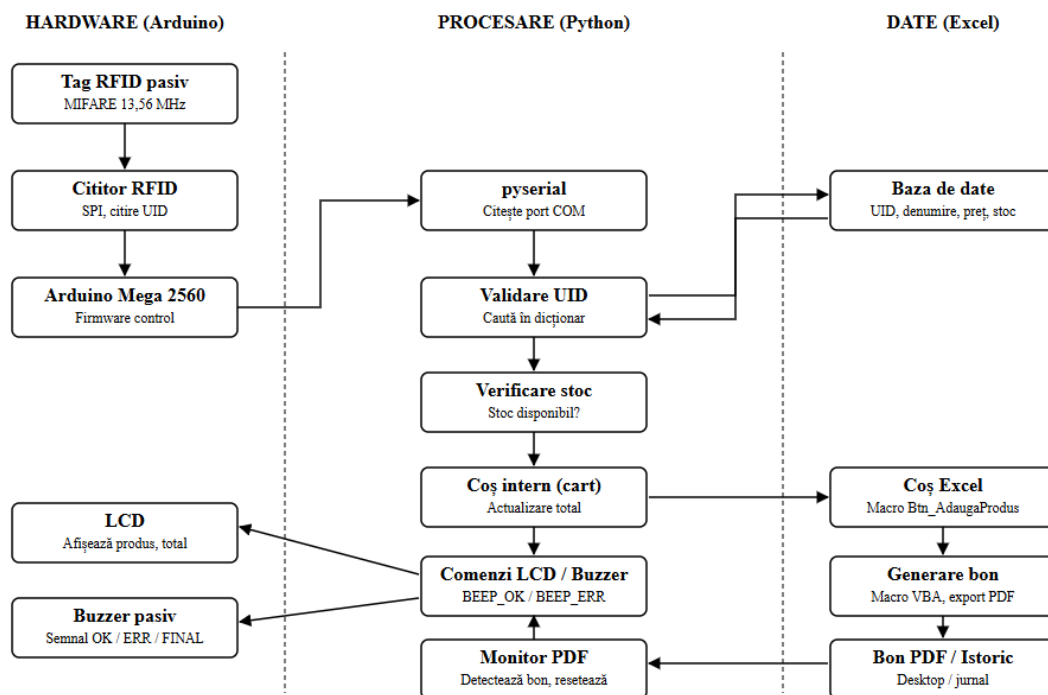


Fig. 1. Architecture of the automatic RFID identification system

The hardware components used are presented in Table 1, together with the role of each within the system. This modular architecture also facilitates future system expansion and the integration of additional hardware or software components.

Table 1. Hardware components		
Component	Specifications	Role in the system
Arduino Mega 2560	5V, 16MHz	Control unit, communicates with the RFID reader, LCD, buzzer and PC
Cititor RFID MFRC522	13.56 MHz, passive tag reading	Reads the UID of the tags attached to products
LCD I2C	2 lines of 16 characters each, 5V	Displays the scanned product, the total and other system messages
Buzzer	5V power supply, digital signal	Acoustically signals scanning, errors and receipt completion
3D-printed case	PLA material, screw-	Protects the hardware components and

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fastened

ensures the portability of the assembly

The case was designed entirely in Autodesk Inventor and then 3D-printed, providing a compact assembly and mechanical protection for all components. All parts are fastened with M3 screws, and the top cover allows access to the RFID reader and the LCD display through dedicated cutouts.

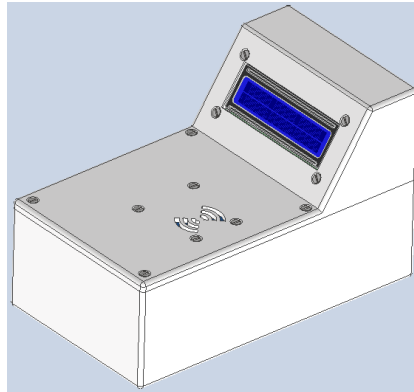


Fig. 2. CAD model of the case in Autodesk Inventor

4. Implementation of the software and hardware components

The implementation of the system was carried out in three stages, according to the three objectives of the paper.

4.1. Implementation of the hardware components

The components were connected according to the communication protocols specific to each one (fig 3).

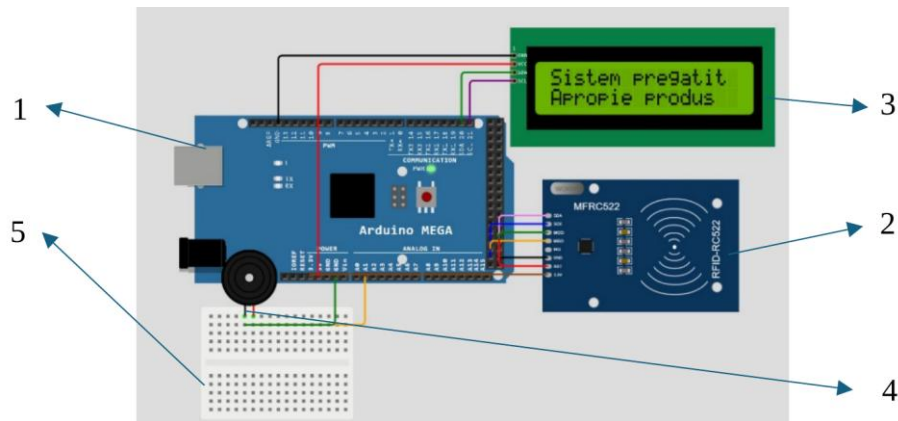


Fig. 3. Wiring diagram of the hardware components

1 - Arduino Mega 2560 - the system's main board, which controls all the other components and communicates with the computer via the USB port.

2 - MFRC522 RFID reader - module that detects RFID tags within its field.

3 - I2C LCD display - screen that displays the system's messages to the user.

4 - Passive buzzer - emits distinct sound signals for different actions.

5 - Breadboard - prototyping board on which power (5V and GND) is distributed to the components.

The MFRC522 RFID reader communicates with the Arduino Mega 2560 board via the SPI interface, using pin 53 for module selection and pin 49 for reset. The LCD display is connected via the I2C bus to the SDA and SCL pins, while the passive buzzer is powered from digital pin A1. All

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components are powered at 5V through the breadboard, and communication with the computer is carried out via the USB port.

4.2. Implementation of the software components

4.2.1. Implementation of the Arduino program

The Arduino program is responsible for initializing the reader, the I2C LCD display and the buzzer [1]. In the main loop, the program reads the RFID tags presented within the reader's field, but also receives commands sent over the serial port from the Python application. For each detected tag, the UID is converted into a hexadecimal character string and transmitted over the serial port. A cooldown mechanism (1200 ms) prevents the repeated reading of the same tag within a short time interval, in order to avoid errors.

The commands received from the computer are of two types: commands for displaying various messages for the customer on the LCD, and commands for emitting the confirmation, error or completion sound signal. Each sound signal has a distinct signature: a short 70 ms beep to confirm a successful scan, two beeps to signal an error, and two long 250 ms beeps to confirm receipt generation. This acoustic feedback system allows the user to quickly identify the state of the system without having to read the message displayed on the LCD.

The code snippet below illustrates the UID reading logic, including the cooldown mechanism that prevents consecutive duplicate readings of the same tag.

```
110     if (!mfr522.PICC_IsNewCardPresent()) return;
111     if (!mfr522.PICC_ReadCardSerial()) return;
112
113     String uid = uidToString();
114     unsigned long now = millis();
115
116     if (uid == lastUID && (now - lastScanMs) < SCAN_COOLDOWN_MS) {
117         mfr522.PICC_HaltA();
118         mfr522.PCD_StopCrypto1();
119         return;
120     }
121
122     lastUID = uid;
123     lastScanMs = now;
124
125     Serial.print("UID:");
126     Serial.println(uid);
```

Fig. 4. Code snippet from the Arduino program implementation

4.2.2. Implementation of the Python application

The Python application (rfidpos.py) represents the “hub” of the system. It uses the pyserial library for communication with the Arduino, pandas for reading the Excel database, and xlwings for live interaction with the workbook open in Microsoft Excel [3]. On startup, the application loads the products from the “Baza de date” (Database) sheet into a dictionary indexed by the tag UIDs, containing the fields: name, price (RON) and stock quantity (pcs).

For each UID read by the Arduino, the application checks whether the product exists in the database and whether it is still in stock. If the product exists and is still available, the UID is written to the ScanInput field in Excel, and the Btn_AdaugaProdus macro is called to update the cart. The internal cart keeps a (price, quantity) pair for each scanned product, and the total is calculated and displayed on the LCD in real time.

The generation of the receipt is detected through a simple mechanism: the application monitors the Desktop folder for the appearance of new PDF files. When a new PDF is detected, the system emits

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the final sound signal, displays the total on the LCD and resets the cart for a new session.

4.2.3. Implementation of the Excel interface

The magazin.xlsm file contains several worksheets: Baza de date (Database) (the product list, with the columns Cod, Denumire, Tip, Cantitate, Locație and Preț), Cos cumparaturi (Shopping Cart) (the operator's visual interface), Bon (Receipt) (the receipt template), Istoric (History) (the transaction log) and Pozitie de stocare (Storage Location) (the physical locations in the store warehouse). The buttons created using VBA macros have the following roles: adding a scanned product, removing a scanned product, and triggering the generation of the receipt in PDF format [4].

The Baza de date (Database) sheet functions as a small inventory management system: for each product, the following are recorded: the RFID tag UID, the name, the type (e.g. jeans, blouse, sweater), the available quantity, the storage location (Raft-femei [Women's Shelf], Raft-bărbați [Men's Shelf], Depozit-R1 [Warehouse R1]) and the price in RON.

The Btn_AdaugaProdus macro implements the logic for adding a product to the cart. When triggered, it reads the UID, looks it up in the Database, and if the product exists, adds it as a new row in the Shopping Cart sheet, or, if the product is already present, increments the existing quantity. The total is automatically recalculated using a SUMPRODUCT formula that multiplies the prices by the quantities for all rows of the cart.

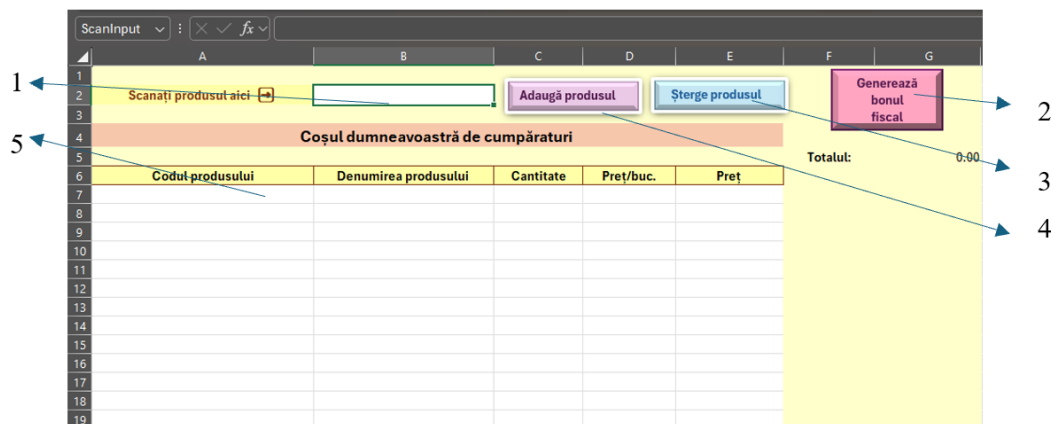


Fig. 5. Excel interface — shopping cart and control buttons

- 1 - Scațați produsul aici (Scan the product here) - the area for manually entering the tag UID.
- 2 - Generează bonul fiscal (Generate receipt) - button that automatically generates the receipt in PDF format, saved to the Desktop, and resets the cart.
- 3 - Șterge produsul (Remove product) - button that removes the scanned product from the current cart and recalculates the total.
- 4 - Adaugă produs (Add product) - button that manually adds a product whose UID was entered in the Scațați produsul aici area.
- 5 - The area with added products - displays the details: code, name, quantity, unit price and total price for each item.

4.3. Flow of actions performed when using the program

The complete flow of a transaction proceeds as follows: the user brings a product labeled with an RFID tag close to the reader, the Arduino reads the UID and sends it over the serial port, the Python application receives the UID, looks it up in the database and checks the available stock; if the product is valid, the UID is written to the ScanInput field in Excel and the Btn_AdaugaProdus macro is called, Excel visually updates the cart and recalculates the total, Python sends the command to activate the buzzer sound and updates the LCD message; when the Generează bonul fiscal button is pressed, the VBA macro exports the cart as a PDF to the Desktop, the Python application detects the appearance of

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the PDF, emits the final sound message and resets the cart for a new product scanning session.

5. Experimental results

The system was tested with an initial database containing five clothing items (jeans, blouse, sweater, bag, tracksuit) priced between 60 and 240 RON. A unique passive RFID UID tag was attached to each product.

In a typical usage scenario, two products were scanned successively (a bag at 60 RON, quantity 2, and a tracksuit at 240 RON, quantity 1), resulting in a total of 360 RON. When the “Generează bonul” (Generate receipt) button was pressed, the Python application automatically generated the PDF receipt on the Desktop, and the LCD displayed the total confirmation message. The entire process, from scanning the first product to saving the PDF, took under 15 seconds.

Fig. 6. Receipt automatically generated in PDF format

Error scenarios were also tested: scanning an unknown tag (a UID that does not exist in the

Magazin RFID			
Sistem POS cu scanare RFID			
BON FISCAL			
Nr: 18			
Data: 11.05.2026 18:24			
Denumire produs	Cant.	Pret/buc.	Total
Trening	3	240	720
Bluză neagră cu paiete	1	90	90
Pulover negru fără umeri	1	80	80
TOTAL DE PLATA: 890 RON			
Va multumim pentru cumparaturi!			

database) causes the message “Produs INEXISTENT” (Product NOT FOUND) to be displayed on the LCD and an error sound signal to be emitted, without affecting the current cart; scanning a product whose stock is depleted displays “STOC EPUIZAT” (OUT OF STOCK) and allows the operator to continue with other products. Thus, the system remains robust and allows operation to continue even in the presence of exceptional situations.



Fig. 7. The message displayed on the LCD when stock is depleted

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6. Conclusions

This paper presented the design and implementation of an automatic RFID-based product identification system. The main original contributions of the paper consist of: building a case designed in Autodesk Inventor and 3D-printed, integrating the identification hardware with an Excel interface that is easy for the client to use, automating the transaction completion process through automatic detection of receipt generation, and implementing a real-time stock management mechanism.

The results obtained confirm, on a prototype scale, the benefits demonstrated in industry. Studies by the RFID Research Center (University of Arkansas, in collaboration with Walmart) showed an improvement of ~13% in inventory accuracy and a 96% reduction in inventory counting time compared to barcode-based systems [6]. The ECR report on 10 European retailers indicated an increase in inventory accuracy from 65-75% to 93-99% [7], while Uniqlo and Zara reported a ~50% reduction in checkout time through RFID self-checkout [8]. The proposed system implements the same principle of automatic UID reading and instant cart updating, at a total hardware cost of less than 200 RON, making it especially useful for educational applications or small stores.

Future research directions include: extending the database through cloud synchronization, integrating a contactless payment module, replacing Excel with a web application, and switching to UHF frequency, which would allow simultaneous reading of the entire cart, a solution adopted by Uniqlo and Decathlon [9], [10]. The developed prototype demonstrates that RFID technology can be implemented using accessible components while maintaining reliable product identification and stock control. Overall, the system provides a practical foundation for further development toward a complete automated retail management solution.

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8. Notations

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RFID = Radio Frequency Identification;

UID = Unique Identifier;

I2C = Inter-Integrated Circuit;

VBA = Visual Basic for Applications;

PDF = Portable Document Format;

CAD = Computer-Aided Design;

PLA = Polylactic Acid;

LCD = Liquid Crystal Display;

ECR = Efficient Consumer Response;

UHF = Ultra High Frequency;

SPI = Serial Peripheral Interface;

USB = Universal Serial Bus.

MODELING AND TRAJECTORY PLANNING FOR AN AUTONOMOUS MOBILE ROBOT AND INDEPENDENTLY LAUNCHED OBJECTS

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ABSTRACT: *This paper addresses the design and implementation of an autonomous mobile robotic system capable of collecting and launching objects at a fixed target, even while in motion. The primary objective is to optimize launch accuracy by developing a swerve drive platform and a launch mechanism with variable angle and velocity. The paper details the mathematical modeling process of the ballistic trajectory, highlighting the experimental calibration methods required to compensate for real-world dynamic factors. A central point of the research is the localization system based on sensor fusion, which integrates kinematic odometry, an IMU sensor, and computer vision via fiducial markers (AprilTags). The results demonstrate that utilizing the MegaTag2 algorithm and virtual target compensation allows the robot to maintain high impact accuracy, neutralizing cumulative positioning errors and the inertial effects of chassis movement.*

KEYWORDS: *autonomous mobile robot, swerve drive, ballistic trajectory, sensor fusion, localization, AprilTags.*

1. Introduction

The purpose of this paper is to detail the development of a suite of algorithms designed to facilitate and optimize the process of collecting and launching a large number of objects toward a predetermined target. These tasks are performed by an autonomous mobile robot. To make this process efficient, two essential capabilities were identified:

- The robot's capability to hit the target from any point around the basket, within a distance of less than 8 meters;
- The robot's capability to hit the target while moving across the field.

Upon identifying these essential characteristics of the robot, the necessity of developing the following algorithms became evident: localization, trajectory generation for the robot, trajectory tracking, and an algorithm responsible for estimating the trajectory of the launched object.

In addition to the software, it is necessary to develop a robust physical platform capable of providing mobility, speed, and repeatability. To ensure the highest possible mobility, an omnidirectional chassis and a launch mechanism equipped with two types of adjustments are required: distance adjustment and direction adjustment.

2. State of the art

The current state of the art in the localization of autonomous mobile robots is dominated by sensor fusion techniques aimed at eliminating the "drift" errors specific to kinematic odometry. While traditional methods based on encoders suffer from wheel slippage, recent research proposes using AprilTag fiducial markers as absolute reference points in controlled environments [3]. Modern implementations, such as systems based on Limelight devices, utilize the MegaTag2 algorithm to combine visual data with data from inertial measurement units (IMUs). This approach allows constraining the rotation axes in the 3D position calculation, offering significantly higher stability compared to standard Perspective-n-Point (PnP) algorithms. According to WPILib documentation, integrating a Kalman filter or retroactive correction algorithms based on timestamps is essential to compensate for video processing latency. Thus, by synchronizing vision data with the chassis movement history, the millimeter-level precision required for ballistic launches under dynamic conditions is achieved [1].

3. Modeling and implementation of the physical platform

The first and most important subsystem of this robot is represented by the chassis. It provides the full mobility of the robot and constitutes the structural foundation upon which the entire assembly is built.

In our case, the chassis consists of two main components:

- aluminum structural profiles;
- "swerve" modules.

The structural profiles are 7075 aluminum rectangular tubes arranged to form a square frame. A "swerve" module is mounted in each corner of this frame. The "swerve" module is a mechanical assembly designed to allow a wheel to be oriented to an unlimited number of degrees directly on the spot while being driven by a motor. This movement is achieved using two motors: one responsible for turning ("turn") and the other responsible for wheel rotation ("drive").



Fig. 3.1. "Swerve" module



Fig. 3.2. aluminum structural profiles

The second subsystem is responsible for launching the objects. The launched objects are spheres made of a dense foam. They are flexible and exhibit a high coefficient of friction when in contact with rubber surfaces. Given the properties of the balls, the operating principle of the launcher is relatively simple: the balls are inserted between a fixed wall and a moving wheel that rotates continuously at high speed. The working principle is similar to that used in tennis ball launching machines. Two distinct solutions were identified to achieve the two types of adjustments: distance adjustment and direction adjustment.

Distance adjustment

To modify the distance at which an object is thrown, varying its initial velocity is sufficient. However, given the wide range of positions from which a launch is desired, it is

necessary to control the shape of the parabola described by the ball's ballistic trajectory. An efficient method of trajectory control consists of modifying the launch angle in the vertical plane.

This adjustment is achieved by replacing the fixed wall with a movable one, shaped as an arc of a circle, which slides along a circular trajectory around the moving wheel. This solution provides an angle adjustment range of 34° (between 47° and 71°), a value subsequently confirmed as sufficient for the proposed application.

Direction adjustment

Direction adjustment is relatively simple and is based on a principle similar to that used in tank turrets. The solution involves mounting the launch system on a rotating platform capable of providing a full 360° rotation.

To constrain all degrees of freedom except for rotation around the Z-axis, an assembly consisting of five bearing packs, two bearing rings, and one fixed ring was chosen. Each bearing pack consists of a radial bearing positioned between two thrust bearings with an increased outer diameter. The five packs are arranged uniformly along the circumference of a circle and are supported by the two bearing rings. The fixed ring features an inner cylindrical surface in tangent contact with the five radial bearings. These contacts ensure translation constraints on the X and Y axes. The thrust bearings serve to constrain rotations around the X and Y axes, as well as translation on the Z axis.

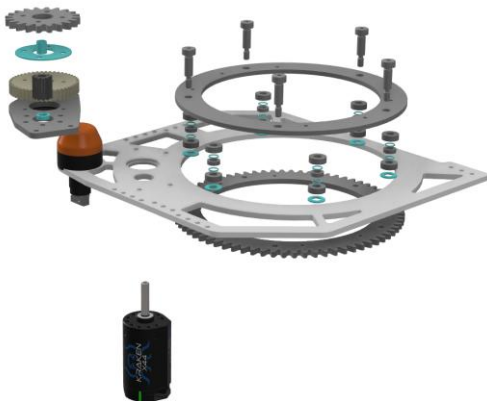


Fig. 3.3. "Turret" exploded view



Fig. 3.4. CAD model of the launcher

4. Mathematical modeling of launcher behavior

The first step of this phase consists of establishing the parameters taken into account, as well as the simplifications applied to the physical model. The trajectory of the ball is defined by two primary input variables: the velocity imparted to the ball and the launch angle. These variables correspond to the rotation speed of the wheel and the positioning angle of the movable wall, respectively.

However, there are other factors that influence the relationship between wheel speed and the velocity transferred to the ball, such as the compression between the wheel and the wall, the friction coefficient between the wheel and the ball, the friction coefficient between the ball and the wall, the rigidity of the ball, etc.

It was decided not to explicitly include these factors in the calculation formula for the velocity imparted to the ball. Instead, an initial approximation was made, to be validated experimentally and corrected later based on a set of measurements. Thus, the result obtained through the theoretical model is multiplied by an experimentally determined correction coefficient.

The resulting formula takes the wheel radius, its angular velocity, and the correction

coefficient as input parameters.

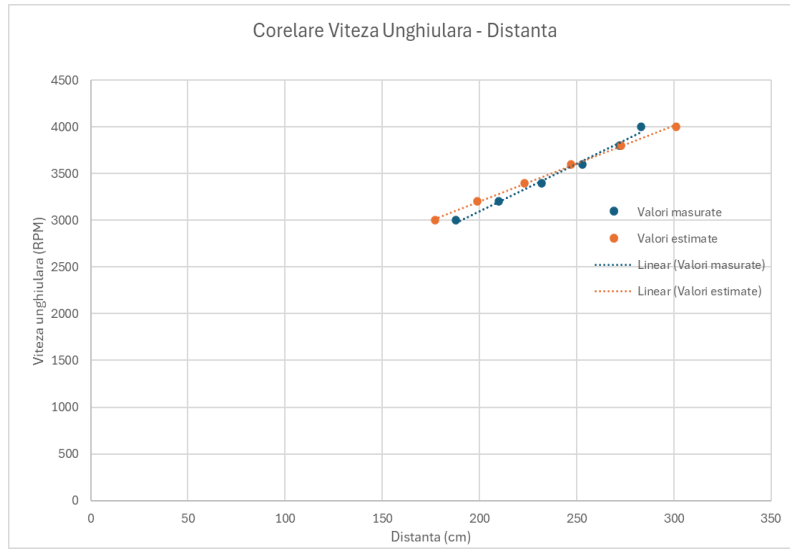


Fig. 4.1. The plot used during the correction coefficient tuning

Another important simplification applied to the mathematical model is ignoring aerodynamic effects. Thus, it was considered that gravity is the only force acting on the ball during flight.

An important problem encountered during the development of the trajectory generation algorithm was that an infinite number of parabolas are possible between point A and point B. Some of these cannot be practically realized, while others are more advantageous because they offer a larger margin of error. Trajectories with an entry angle close to 90° offer the greatest tolerance, which is why the maximum height of the apex was chosen as an additional parameter to determine a unique trajectory.

This choice was made because, as long as the launch height, target impact height, and maximum trajectory height remain constant, the time the ball spends in the air remains the same, regardless of the distance traveled. This property significantly simplifies the algorithm when the robot's velocity relative to the target is also factored in.

In practice, maintaining a constant maximum height is achieved by keeping the vertical component of the velocity constant and modifying the horizontal component. Thus, the distance traveled can be controlled without altering the maximum height of the trajectory. The distance is determined by multiplying the horizontal velocity, considered constant, by the flight time.

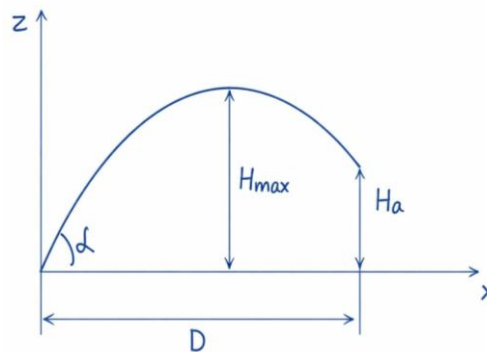


Fig. 4.2. Ball trajectory

The first part of the algorithm computes the vertical component of the velocity based on the imposed maximum height of the trajectory. This calculation uses the velocity law, assuming that the final velocity at the apex is equal to 0, and the acceleration is gravitational.

$$v(t) = v_i \Rightarrow t_1 = \frac{v_i}{g} \quad (1)$$

$$\frac{v_i}{2} \cdot t_1 = h_{max} \Rightarrow v_i = \sqrt{2gh_{max}} \quad (2)$$

Thus, the required vertical velocity and the time elapsed between the launch and reaching the apex of the trajectory are determined. Using the same logic, the time required for the object to cover the distance between the apex and the target height is calculated.

$$v_f = \sqrt{2g(h_{max} - h_{tinta})} \quad (3)$$

$$t_2 = \frac{v_f}{g} \quad (4); \quad t_1 + t_2 = t_{total} \quad (5)$$

To determine the horizontal velocity, the distance is divided by the total flight time. Knowing both the horizontal and vertical components of the velocity, the required resultant velocity and the launch angle of the ball can be easily calculated. From the velocity obtained in this manner, the angular velocity of the motor is then determined using the experimentally derived relationship.

$$V = \sqrt{V_i^2 + V_o^2} \quad (6)$$

$$\alpha = \text{atan}\left(\frac{V_i}{V_o}\right) \quad (7)$$

Determining the turret angle is accomplished by applying the arctangent function to the ratio of the coordinate differences on the X and Y axes between the launcher and the target.

$$\phi = \text{atan}\left(\frac{x_{lansator} - x_{tinta}}{y_{lansator} - y_{tinta}}\right) \quad (8)$$

To establish the coordinates of the launcher in the global reference system, we must use the coordinates returned by the localization algorithm (x_{Robot} , y_{Robot} , α_{Robot}), which refer to the geometric center of the robot, and the position of the launcher relative to the center of the robot. The angle formed by the y and y' axes is denoted by α_{Robot} .

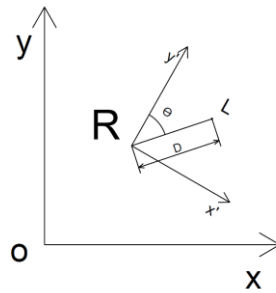


Fig. 4.3. Global and local frames of reference

$$\theta = \text{atan}\frac{x_L'}{y_L'} \quad (9)$$

$$D = \sqrt{x_L'^2 + y_L'^2} \quad (10)$$

$$x_L = x_R + D \sin(\alpha_{Robot} + \theta) \quad (11)$$

$$y_L = y_R + D \cos(\alpha_{Robot} + \theta) \quad (12)$$

When the robot is not static, the algorithm no longer functions correctly because the horizontal velocity of the launcher is also transmitted to the ball. To compensate for this effect without altering the mathematical model of the trajectory, a compensation is performed by shifting the target. Thus, if the robot moves to the left, the target is virtually shifted to the right by an amount equivalent to the robot's velocity.

$$v_{xL} = v_{xL} + D \sin(\alpha_{Robot} + \theta) \quad (13)$$

$$v_{yL} = v_{yL} + D \cos(\alpha_{Robot} + \theta) \quad (14)$$

$$\Delta x = v_{xL} \cdot t_{total} \quad (15)$$

$$\Delta y = v_{yL} \cdot t_{total} \quad (16)$$

$$x_{tintavirtual} = x_{tintareal} + \Delta x \quad (17)$$

$$y_{tintavirtual} = y_{tintareal} + \Delta y \quad (18)$$

5. Localization and Global Position Estimation of the Robot

5.1. Localization System Architecture

To implement the on-the-move launch algorithm presented above, determining the global coordinates of the robot is required. Launch accuracy directly depends on the current state of the chassis, as any localization error propagates into the ballistic trajectory calculation.

The proposed architecture is based on sensor fusion, integrating high-frequency data from internal sensors (swerve module odometry and the IMU sensor) with absolute measurements provided by the computer vision system.

Although odometry offers a fast update rate, it is prone to cumulative errors over time ("drift") caused by wheel slippage. To correct these deviations, the system uses three Limelight 4 cameras that detect fiducial markers (AprilTags) on the field and target, providing absolute reference points. Fusing this data ensures an accurate estimation of the global position, which is essential for the proper functioning of the previously defined mathematical models [1].

5.2. Kinematic Odometry and Internal Sensor Fusion

Prima componentă a sistemului de localizare este reprezentată de odometria cinematică, o metodă de estimare a poziției relative a robotului prin integrarea în timp a mișcărilor măsurate la nivelul fiecărui modul Swerve. Cinematica robotului se bazează pe o dispunere simetrică a celor patru roți, formând un pătrat cu distanța de la centru la fiecare modul de 10 inci. Fiecare modul este echipat cu două motoare TalonFX (pentru tracțiune și direcție) și un encoder absolut CANcoder.

Pentru a calcula vectorul de viteză al centrului de greutate al șasiului, definit prin componentele v_x, v_y și viteza unghiulară ω , se utilizează un model cinematic direct (Forward Kinematics) al platformei omnidirecționale. Cunoșcând raza roților și rapoartele de transmisie, vitezele unghiulare ale motoarelor sunt transformate în viteze liniare. Poziția curentă a robotului, definită de coordonatele (x_{Robot}, y_{Robot}) , este actualizată iterativ prin integrarea acestor viteze în raport cu timpul:

The first component of the localization system is kinematic odometry, a method of estimating the robot's relative position by integrating the movements measured at each swerve module over time. The robot's kinematics are based on a symmetrical layout of the four wheels, forming a square with a distance of 10 inches from the center to each module. Each module is equipped with two TalonFX motors (for drive and steering) and a CANcoder absolute encoder.

To calculate the velocity vector of the chassis' center of gravity, defined by the components v_x, v_y and the angular velocity ω , a forward kinematics model of the omnidirectional platform is utilized. Knowing the wheel radius and gear ratios, the angular

velocities of the motors are transformed into linear velocities. The current position of the robot, defined by the coordinates (x_{Robot}, y_{Robot}) , is iteratively updated by integrating these velocities with respect to time:

$$x_t = x_{t-1} + (v_x \cos \alpha_{Robot} - v_y \sin \alpha_{Robot}) \Delta t \quad (19)$$

$$y_t = y_{t-1} + (v_x \sin \alpha_{Robot} + v_y \cos \alpha_{Robot}) \Delta t \quad (20)$$

To mitigate error accumulation caused by traction loss, the software preventively limits the stator current of the drive motors. Although this mechatronic limitation significantly reduces slippage, cumulative errors still require absolute corrections, periodically supplied by the camera system.

5.3. Computer Vision System Based on Fiducial Markers

To compensate for cumulative odometry errors, the system utilizes a computer vision network composed of three Limelight 4 smart cameras. These are mounted on three of the four sides of the chassis to maximize the field of view and minimize blind spots.

Because the chassis rotates independently to orient the collection mechanism, the extended visual coverage guarantees that, regardless of the robot's angle, at least one camera maintains a line of sight with the fiducial markers (AprilTags) fixed on the target or in the surroundings.



Fig. 5.1 ApriTag



Fig. 5.2 Limelight4 Camera

Each camera processes video frames to identify these tags, whose global coordinates are precisely predefined. By analyzing the perspective of the tag in the image, the cameras generate absolute estimates of the robot's position in space. These independent measurements serve as references that negate the drift of the internal odometry.

5.4. MegaTag2 Algorithm and Data Fusion

The system utilizes the MegaTag2 algorithm to extract global coordinates. Unlike classical Perspective-n-Point (PnP) methods, which deduce camera orientation purely visually and are vulnerable to mathematical ambiguities, MegaTag2 integrates the orientation and angular velocity read directly from the IMU sensor. This constraint on the rotation axis generates a much more precise and stable 3D position estimation [2].

Visual data is integrated into the odometry via a state filter. The confidence level of the measurements is dynamically computed: it is penalized by an increase in distance (over 5 meters) and linear velocity, but it benefits from the simultaneous detection of multiple markers. To ensure stability, measurements are rejected if marker ambiguity is high or if the robot is rotating aggressively, a situation that introduces optical distortions (motion blur).

Finally, data fusion includes processing latency compensation. Using the timestamp of

each video frame, the algorithm retroactively corrects the position history. Consequently, the launching system benefits from a continuous and perfectly synchronized position with the physical movement of the chassis.

6. Conclusions

This paper highlighted the complexity of designing an autonomous robotic system, offering a practical perspective on how mathematical modeling can translate unpredictable physical processes, such as ballistic trajectories, into precise control algorithms. A fundamental takeaway was the necessity of adjusting theoretical models using experimental correction coefficients, a method that allows compensating for factors difficult to quantify (friction, compression) to achieve the required accuracy under dynamic operating conditions.

At the same time, the project demonstrated the importance of data fusion from multiple sensors (odometry, IMU, and computer vision) to solve the global localization problem; integrating them through algorithms like MegaTag2 showed how absolute visual data can cancel out the cumulative errors of internal sensors. Ultimately, correlating the localization system with the launch system confirmed that the success of an autonomous mobile platform resides in the perfect synchronization between the robot's kinematics and the mathematical model of the work task.

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DEVELOPMENT OF AN AUTOMATED STORAGE SYSTEM FOR ROBOTICS COMPONENTS BASED ON RFID TECHNOLOGY

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***ABSTRACT:** This paper presents the development of an automated storage system for robotics components, based on RFID technology for identifying and confirming system positions. The experimental platform reproduces, at a reduced scale, the principals of an AS/RS system used in industrial logistics, demonstrating how technical components can be stored, retrieved and handled automatically. The system integrates a three-axis mechanical structure, a control panel, sensors and a SCADA interface. Through calibration, return-to-HOME, retrieval and storage commands, the platform allows the simulation of an automated storage flow. The paper highlights the importance of automation, traceability and digital integration in the future development of logistics systems.*

KEYWORDS: AS-RS, RFID, SCADA, Arduino

1. Introduction

The automation of storage and retrieval processes represents one of the important development directions in modern industrial logistics. In an environment where material flows are becoming increasingly faster, and where requirements related to traceability, accuracy and reduced operating times are becoming more demanding, automated storage systems can contribute to a more efficient organization of workspaces and to the reduction of repetitive manual interventions. This direction is relevant not only for large industrial warehouses, but also for laboratories, technical workshops, production areas and spaces where small-sized components are handled.

In the case of robotics components, the correct organization and identification of parts are important because these components may include various elements, such as sensors, electronic modules, actuators, mechanical components and subassemblies used in technical projects. Manual storage of these components can lead to identification errors, time lost searching for parts and difficulties in tracking the position of each item. For this reason, the use of an automated storage system, supported by an identification technology such as RFID, can represent a practical solution for increasing control over the component flow.

This paper presents the development of an automated storage system for robotics components based on RFID technology. The proposed system is built as an experimental AS/RS platform, which reproduces, at a reduced scale, the principles of an automated storage and retrieval system. The platform consists of a three-axis mechanical structure, an RFID identification system for position confirmation, a control panel with an Arduino Mega-based control unit and a SCADA interface developed in Django and running on a Raspberry Pi 5.

The main objective of the paper is to design and build a functional platform capable of performing calibration, positioning, retrieval and storage operations in locations defined by levels and columns. Through this approach, the paper aims to demonstrate how an AS/RS solution can be adapted to an experimental scale while preserving the essential elements of an automated logistics system.

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By developing this system, the paper highlights the connection between industrial logistics, automation, applied robotics and digital identification. The platform is not intended to replace a complete industrial system, but to provide a functional and educational prototype through which the principles of automated storage can be studied. At the same time, the project shows how accessible technologies, such as microcontrollers, RFID and web interfaces, can be integrated into a system that is useful for understanding the future of intelligent logistics.

2. Overview of Existing AS/RS Solutions

At present, automated storage and retrieval systems have become an important component in the development of industrial logistics, especially in fields where large product volumes, small parts or containers are handled. These systems are used to reduce search times, increase storage density, improve traceability and reduce dependence on repetitive manual operations.

Modern AS/RS systems are no longer limited to mechanisms that move between storage racks. They are integrated assemblies that include storage structures, robots, sensors, control software, monitoring systems and operator interfaces. Depending on the application, they can be used in warehouses, production areas, pharmacies, the automotive industry, spare parts logistics or in the storage of small-sized components.

2.1. AS/RS Solutions Used in Industry

In the industrial field, there are several types of automated storage systems, each adapted to a specific type of load, available space and logistics flow. These systems can be found in warehouses, distribution centers, factories, the automotive industry, electronics, e-commerce and spare parts management.

Modern industrial solutions are usually complex systems, integrated with management software, sensors, automated handling mechanisms and operator interfaces. They are designed for high productivity and continuous operation, but they involve high costs and are more difficult to analyze completely in an educational environment. Some relevant examples are presented in the following table.

Table 1. Examples of AS/RS solutions used in industry

System / platform	Description
AutoStore	A compact AS/RS system based on a grid structure, where bins are stored vertically and robots move on top of the structure to retrieve products (Fig. 1).
Kardex AS/RS	Automated storage and retrieval solutions used to optimize space, reduce costs and coordinate materials through WMS-type software (Fig. 2).
Daifuku Mini Load AS/RS	An automated system designed for the fast storage and retrieval of containers, boxes and other small loads (Fig. 3).
Modula Lift	An automated vertical storage system used for industrial products, semi-finished goods, spare parts and items that need to be stored in an organized way and accessed quickly (Fig. 4).

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Fig. 1. Representative image of the AutoStore system

Source: StrongPoint Product Review [1]



Fig. 2. Representative image of a Kardex AS/RS solution

Source: Kardex Website [2]

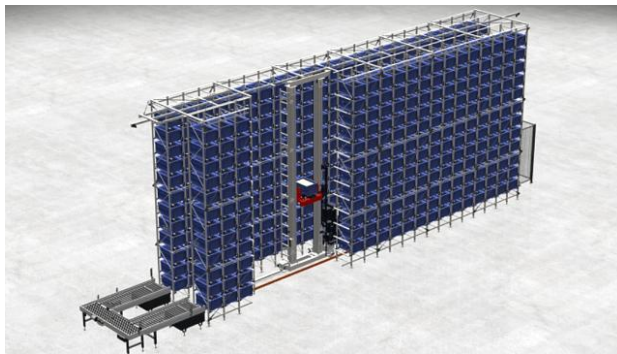


Fig. 3. Representative image of the Daifuku Mini Load AS/RS system

Source: Daifuku Intralogistics Solutions [3]



Fig. 4. Representative image of the Modula Lift system

Source: Modula Vertical Lift Product [4]

2.2. Educational and Experimental Platforms

In addition to industrial systems, there are also educational and experimental platforms developed for studying logistics automation, RFID technology and the principles of Industry 4.0. These systems are used in universities, laboratories and technical environments where the focus is placed on the practical understanding of automated system operation.

Educational platforms have the advantage of allowing direct observation of the relationship between mechanics, sensors, control, actuators and software. However, many of these platforms are predefined commercial solutions, where the user mainly interacts with an already developed system rather than designing and building one from the ground up. For this reason, developing an experimental platform brings important practical value, because it makes it possible to go through the entire process: design, assembly, integration, programming and testing.

System / platform
Festo Didactic CP-F-ASRS32-P

Table 2. Examples of educational and experimental platforms

Description
An educational AS/RS platform for pallets, equipped with a Cartesian robot for automated storage and

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SMC LOG-200 RFID Logistics Trainer

Festo CP Lab / CP Factory

retrieval (Fig. 5).

A didactic platform focused on the study of RFID technology in a logistics application (Fig. 6).

A modular educational system for learning the principles of Industry 4.0, automation and connected production (Fig. 7).



Fig. 5. Festo Didactic CP-F-ASRS32-P educational platform
Source: Festo CP-F-ASRS32-P Manual [5]



Fig. 6. SMC LOG-200 RFID Logistics Trainer platform
Source: Website SMC International Training [6]



Fig. 7. Festo CP Lab / CP Factory educational system
Source: Website Festo Didactic [7]

Table 3. Comparison between existing AS/RS solutions and the proposed experimental platform

Criterion	Industrial AS/RS systems	Educational platforms	Proposed AS/RS platform
Purpose	Industrial operation	Technical training	Applied research
Size	Industrial scale	Laboratory scale	Laboratory scale
Handling type	Robots, lifts, shuttles	Didactic stations	Three-axis mechanism
Identification	WMS, codes, sensors	RFID, PLC, sensors	RFID for C1-C6 and L1-L5
Control	Programmable systems	Educational modules	Arduino Mega
Interface	Industrial software	HMI / web server	SCADA interface

From the comparison presented above, it can be observed that the proposed AS/RS platform is not intended to compete directly with industrial systems, as these are designed for high productivity and continuous operation. The role of the developed platform is experimental and educational, being oriented toward the practical understanding of how an automated storage system can integrate mechanics, RFID identification, device control and a SCADA interface. Therefore, the project takes the general principles of industrial AS/RS systems and adapts them into an accessible form for study, testing and validation within an applied research paper.

3. Proposed Experimental Platform

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This paper proposes the development of an experimental AS/RS platform for the automated storage and retrieval of robotics components. The system was designed to reproduce, at a reduced scale, the principles of an automated storage system used in industrial logistics, while preserving the essential functions: location addressing, controlled movement on axes, position identification, retrieval/storage of load units and operation monitoring through a digital interface.

Unlike the industrial systems presented previously, the developed platform is not intended for operation in a real warehouse, but for the experimental validation of AS/RS principles in a controlled environment. The value of the project lies in the practical integration of several subsystems: mechanics, electronics, control program, RFID and software interface. Thus, the platform allows direct observation of how a command transmitted by the operator is transformed into mechanical movement, RFID confirmation and state update in the SCADA interface.

The useful storage capacity of the platform can be expressed as the product between the number of levels and the number of normal rack columns:

$$N = nL \cdot nC = 5 \cdot 5 = 25 \text{ locations} \quad (1)$$

where nL represents the number of levels, and nC represents the number of columns used for storage. Position C6 is not included in the calculation, because it is reserved for the HOME position, defined as L2C6.

3.1. General System Architecture

The system architecture is organized on several functional levels. The operator interacts with the SCADA interface, which transmits commands to the Arduino Mega through serial communication. The Arduino Mega interprets the commands, controls the drivers and motors, receives information from the RFID readers and sends the system status back to the interface.

The AS/RS platform (Fig. 8) is organized into several functional layers, from the operator's interaction with the SCADA interface to the physical control of the mechanism (Fig. 9, 10). The relationship between the main components of the system is presented in (Fig. 11).

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Fig. 8. Physically developed experimental AS/RS platform
Source: own photography

```

if (s == "CALIBRARE") {
    startCalibration();
    return;
}

if (s == "ACASA") {
    if (!systemCalibrated) {
        Serial.println("SISTEMUL NU A FOST CALIBRAT. CALIBREAZĂ-L ÎNTÂI.");
        return;
    }
    startRackJobGoHome();
    return;
}

if (s.startsWith("PREIA")) {
    if (!systemCalibrated) {
        Serial.println("SISTEMUL NU A FOST CALIBRAT. CALIBREAZĂ-L ÎNTÂI.");
        return;
    }

    int L = -1, C = -1;
    parseLC(s, L, C);
    startRackJobPreia(L, C);
    return;
}

if (s.startsWith("PUNE")) {
    if (!systemCalibrated) {
        Serial.println("SISTEMUL NU A FOST CALIBRAT. CALIBREAZĂ-L ÎNTÂI.");
        return;
    }
}
    
```

Fig. 9. Fragment of the control
program for interpreting the serial
commands of the AS/RS platform
Source: own contribution

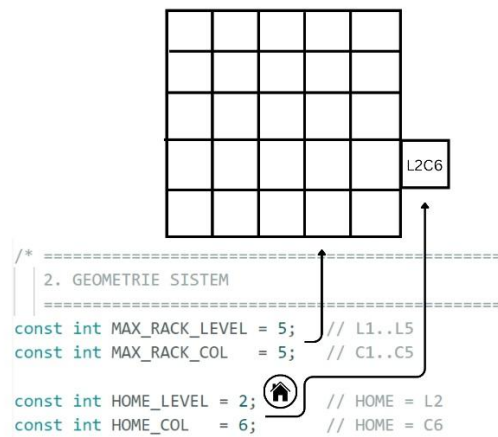


Fig. 10. Fragment of the control program defining the
logical geometry of the AS/RS platform
Source: own contribution

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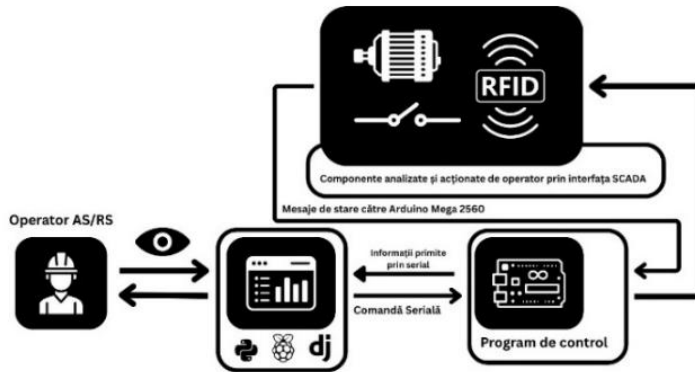


Fig. 11. General hardware-software architecture of the AS/RS platform
Source: own contribution

3.2. Main Subsystems of the Platform

The platform can be divided into several subsystems. Each subsystem has its own role, but the operation of the system results from their integration into a common architecture.

Table 4. Main subsystems of the AS/RS platform

Subsystem	Role within the platform
Mechanical structure	Supports the motion axes, the storage area and the retrieval mechanism.
Horizontal axis	Moves the mechanism between the rack columns.
Vertical axis	Moves the mechanism between the rack levels.
Depth axis	Allows the mechanism to enter and retract from the rack location.
RFID system	Confirms positions on the horizontal and vertical axes through RFID tags.
Control panel	Groups the power supply, protection elements, drivers, relays and connections.
Arduino Mega	Controls the movements, interprets the commands and manages the main logic.
Raspberry Pi 5	Runs the SCADA interface developed in Django.
SCADA interface	Allows command, monitoring, status display and event tracking.

3.3. Mechanical Structure and System Positions

From a mechanical point of view, the AS/RS platform is built as a three-axis handling system. The horizontal axis allows movement between columns, the vertical axis allows movement between levels, and the depth axis allows the mechanism to enter and retract in relation to the rack. By combining these movements, the system can reach a defined location and perform a retrieval or storage operation.

The storage locations are defined by combinations of the form $LxCy$, where Lx represents the level and Cy represents the column. For the experimental rack, the normal locations are defined by levels L1-L5 and columns C1-C5. Position C6 is reserved for the special HOME position, defined as L2C6, and is not treated as a normal location (Fig. 10).

3.4. Role of RFID Technology

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RFID technology is used to confirm the positions of the mechanism. The RFID tags are mounted along the travel paths of the axes, with each tag being associated with a logical position in the system. For the horizontal axis, tags are used for columns C1-C6, while for the vertical axis, tags are used for levels L1-L5 (Table 5.).

Position confirmation can be expressed through a logical validation condition. A position is considered correct if the level and column read through RFID correspond to the commanded level and column:

$$P_{valid} = (L_{RFID} = L_{commanded}) \wedge (C_{RFID} = C_{commanded})$$

where L_{RFID} and C_{RFID} represent the level and column read through RFID, while $L_{commanded}$ and $C_{commanded}$ represent the level and column requested through the command.

Table 5. Role of RFID tags in the AS/RS platform

RFID area	Identified positions	Role
Horizontal RFID	C1, C2, C3, C4, C5, C6	Confirms the current column on the horizontal axis.
Vertical RFID	L1, L2, L3, L4, L5	Confirms the current level and the HOME level.
HOME position	L2C6	Represents the reference position of the system.

3.5. Main System Commands

The platform is controlled through a set of serial commands transmitted from the SCADA interface to the Arduino Mega. The main commands are used for calibration, return to the HOME position, positioning, retrieval, storage and stopping.

Table 6. Main commands used in the AS/RS platform

Command	Role
CALIBRARE	Initializes the system and establishes the reference position.
ACASA	Sends the system to the HOME position.
PREIA LxCy	Executes the retrieval operation from the selected location.
PUNE LxCy	Executes the storage operation in the selected location.
POS?	Requests the current position of the system.
STOP	Stops the current operation in a controlled way.
SS	Activates the logical safety stop.

The PREIA and PUNE commands are accepted only for normal rack locations, namely L1-L5 and C1-C5 (Fig. 10). Position C6 is reserved for HOME and is not used as a normal storage position. From a logical point of view, the PREIA and PUNE commands are accepted only for normal rack locations:

$$L \in \{1,2,3,4,5\}, C \in \{1,2,3,4,5\} \quad (2)$$

Through this rule, position C6 is excluded from storage and retrieval commands, being reserved exclusively for the HOME position.

3.6. Difference from the Analyzed Platforms

The proposed platform differs from the analyzed systems because it is not a ready-made commercial system, but a prototype designed, built and integrated as part of the paper. Compared to industrial systems, the platform has reduced dimensions and an experimental purpose. Compared to commercial educational platforms, the system offers the advantage that

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each subsystem was selected, assembled, connected and tested within the project (Fig. 5, 6, 7).

This difference is important because it allows a complete understanding of the development process of an automated system: from mechanical design and component selection to motion control, RFID reading and the development of the SCADA interface. In this way, the paper does not present only the use of an existing piece of equipment, but the development of a functional experimental platform adapted to the storage of robotics components.

4. Tests and Results

Within this paper, the testing of the AS/RS platform was carried out in order to verify the integrated operation of the mechanical, electrical, electronic, control and software subsystems. Since the system has an experimental character, the tests focused on confirming the main commands, verifying the HOME position, reading the RFID tags and observing the behavior of the platform in stopping or logical blocking situations (Fig. 12).

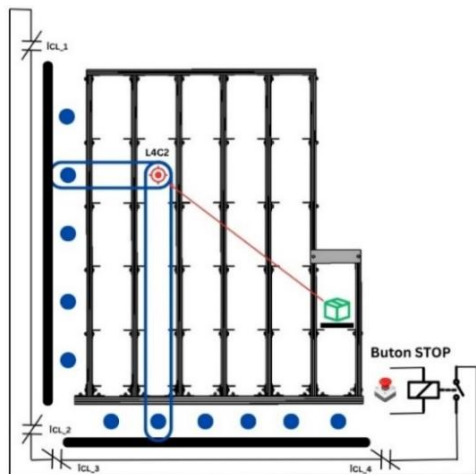


Fig. 12. Functional representation of the movement path toward location L4C2 and of the stopping elements of the AS/RS platform

Source: own contribution

Testing was organized in stages, starting from simple calibration and positioning commands and continuing with automatic retrieval and storage sequences. In this way, it was possible to observe whether the SCADA interface correctly transmits the commands to the Arduino Mega, whether the control program interprets the received commands and whether the mechanism executes the movements in the established order (Fig. 11).

			Table 7. Testing scenarios for the AS/RS platform
No.	Scenario	Command	Expected result
1	System calibration	CALIBRARE	Return to the HOME position = L2C6.
2	Return to HOME	ACASA	Controlled positioning in L2C6.
3	Movement to a location	LxCy	Position confirmed through RFID reading.
4	Retrieval from a location	PREIA LxCy	Retrieval of the experimental load unit.
5	Storage in a location	PUNE LxCy	Storage of the experimental load unit.
6	Controlled stop	STOP	Cancellation of the current command via software.

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- | | | | |
|---|---------------------|----|--|
| 7 | Logical safety stop | SS | Stopping and logical blocking of the system. |
|---|---------------------|----|--|

5. Conclusions

The paper presented the development of an automated storage system for robotics components, based on RFID technology. The system was developed as an experimental AS/RS platform, which reproduces, at a reduced scale, the principles of an automated storage and retrieval system used in industrial logistics.

The main contribution of the paper consists in the integration of a functional physical platform, composed of a three-axis mechanical structure, a control panel and a SCADA interface. Through this integration, the commands transmitted by the operator can be transformed into real movements of the mechanism, while the positions are confirmed through RFID tags.

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Study of Spatial Trajectories of Transport Systems in a Warehouse Using HILBERT Curve AND QR CODES

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SUMMARY: This paper presents a study of warehouse navigation methods based on the Hilbert Curve and the Snake path approach. The Hilbert curve was analyzed as a structured and scalable trajectory for efficient space coverage, while the Snake path was evaluated as a simpler and more intuitive alternative. A comparative analysis between the two methods was performed based on efficiency, adaptability, and implementation complexity. To support the study, a C++ program was developed for generating and calculating Hilbert trajectories, allowing the simulation of robot movement in a logistics warehouse. The results highlight the advantages and practical applications of both approaches in automated logistics systems.

KEYWORDS: Hilbert Curve, path, displacement, optimization.

1. Introduction

Within logistics warehouses, the movement of products, operators, or automated systems represents an important part of the activities carried out daily. The way in which routes are selected and organized can directly influence working time, resource consumption, and the overall efficiency of logistics processes. With the development of automation technologies and the emergence of mobile robots, finding increasingly efficient movement methods has become a topic of growing importance.

In this paper, several movement methods that can be used in a logistics warehouse were analyzed, with a particular focus on the Hilbert curve and the Snake-type path. The aim was to present how the Hilbert curve works, why it can be useful in such an environment, and what its main advantages are compared to other traversal methods. At the same time, a comparison was also made with the Snake path and graph-based movement, in order to observe more clearly in which situations each method may be more suitable.

To better understand the practical applicability of the Hilbert curve, a program written in C++ was also developed, allowing the generation of routes for different curve orders and providing a visual representation of the curve. In this way, it becomes easier to observe how such a method could be implemented in a real warehouse environment.

In the final part of the paper, several possible development directions were also included, such as the analysis of crowded areas within a warehouse using heatmaps and their integration with the Hilbert curve and QR codes, for a more efficient organization of movements and better coordination of logistics systems.

2. Current state of research

At present, within logistics warehouses, the movement of products and automated systems represents an important part of operational processes. With the development of automation, more activities such as internal transport, product scanning, stock

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verification, and picking are carried out using automated mobile robots (AMR), AGVs, and other intelligent systems. For this reason, choosing an efficient movement method inside the warehouse has become an important issue.

In practice, for point-to-point movement between two locations, static algorithms or graph-based methods are frequently used, since they allow the calculation of a minimum route between different points within the warehouse. This approach is useful when a system must quickly reach a specific destination or when certain areas need to be avoided.

At the same time, for activities that involve complete or repeated traversal of the warehouse, such as scanning, verification, or inventory operations, other types of routes are also used. One of the simplest methods is the Snake path, which allows the entire space to be covered in an intuitive and easy-to-implement manner.

In addition to these methods, this paper also analyzes the method based on the Hilbert fractal curve, which offers a different way of organizing movement. This method allows the continuous traversal of all points within an area, without intersections and without unnecessary returns, each location being visited only once. Due to this property, the Hilbert curve may represent an interesting solution for automated warehouses, especially in repetitive operations or in situations where complete space coverage is required.

Furthermore, the use of heatmap-based representations can contribute to a better organization of movements by providing information about product locations, crowded areas, and work priorities within the warehouse.

3. Movement Methods and Algorithms in a Logistics Warehouse

Within a logistics warehouse, there are various movement methods. These include [1]:

- **Single Order Picking:** This is the simplest method, in which an operator (picker) or an automated system handles a single order and collects it from the warehouse.
- **Batch Picking:** This method involves selecting products for multiple orders simultaneously, grouping them into batches or containers to reduce travel time.
- **Zone Picking:** The warehouse is divided into zones, and each operator or automated system is responsible for a specific area, collecting products from that zone for the corresponding orders.
- **Task Interleaving:** This is an optimization technique managed by a WMS (Warehouse Management System), which combines tasks, for example combining a picking operation with a relocation task, in order to reduce empty travel time and increase operational efficiency.

For most types of movement, the graph-based method is the most efficient way of navigating through a warehouse, since it calculates the exact minimum path required for the operator or automated system responsible for performing the necessary action in the shortest

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possible time. However, there are situations in which the entire warehouse must be traversed, and the use of graph-based methods is no longer strictly necessary.

In such situations, there are several alternative traversal methods, which are presented below.

✓ Hilbert Curve - This is a method based on the well-known Hilbert fractal, discovered in 1891 by the mathematician David Hilbert [2].

A fractal represents a geometric structure characterized by the repetition of similar patterns at different scales. This property, called self-similarity, allows the description of complex forms encountered both in mathematics and in nature.

The Hilbert curve, introduced by the mathematician David Hilbert, is a fractal space-filling curve. It transforms a linear path into a structure that systematically traverses a two-dimensional surface, being used in fields such as computer science, robotics, and route optimization.

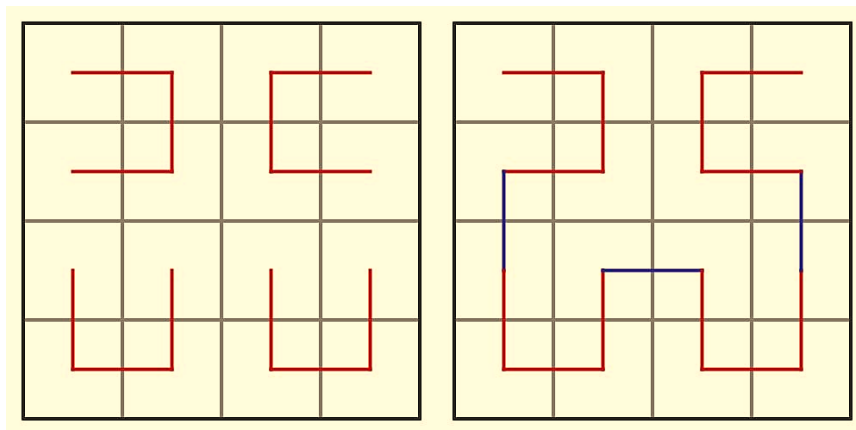


Fig. 1. The formation of the 2nd grade of Hilbert Curve

An important detail related to the Hilbert curve is that it attempts to preserve spatial proximity, meaning that points that are close in physical space also tend to be close in its traversal order. This method is particularly useful when accessing local areas or in applications where reducing unnecessary movement is important.

✓ Snake Curve - The Snake curve is a space traversal method based on sequential movement, in which the path follows parallel lines and changes direction at the end of each line, similarly to the way a snake moves [3].

Below, a graphical representation of the three algorithmic warehouse traversal methods is provided: the graph-based method, the Hilbert method, and the Snake curve.

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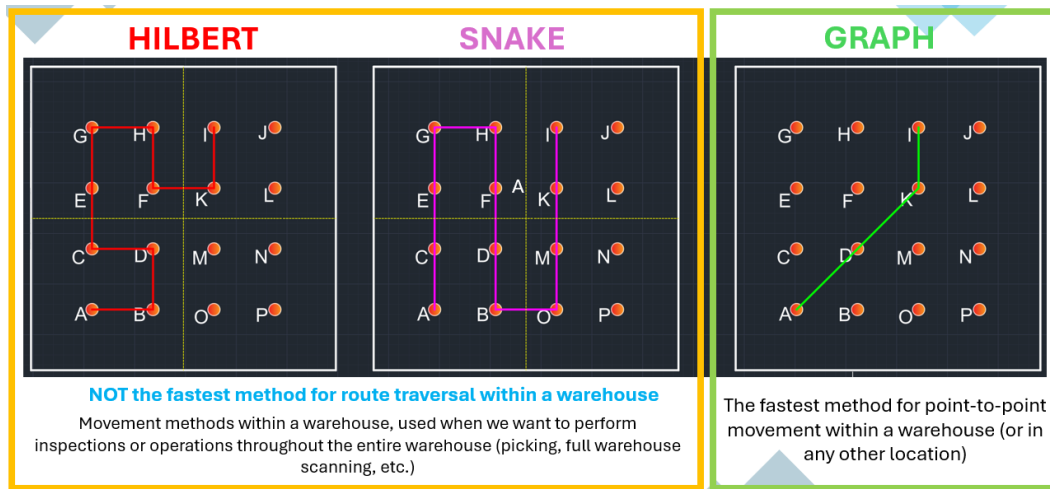


Fig. 2. A visual comparison of the 3 warehouse navigation methods [4]

4. Comparative analysis between Hilbert and Snake Methods

Within intelligent logistics warehouses, the selection of an efficient movement method directly influences traversal time, resource consumption, and operational efficiency.

In this chapter, two modern space traversal methods are analyzed, namely the Hilbert method and the Snake method (a variation of it), to highlight the characteristics of each approach, as well as their advantages, limitations, and differences.

Similarities between the 2 methods:

- Both methods are warehouse spatial traversal methods
- Both methods can be divided into 4 quadrants (each containing 4 points, as shown in the example above)
 - ✓ Bottom left
 - ✓ Top left
 - ✓ Bottom right
 - ✓ Top right
- Both paths can traverse each point exactly once
- Both paths can be adapted to changes in the warehouse layout, such as addition of new nodes or modifications to its dimensions.

Differences in which the Hilbert Curve has clear advantages:

- The Hilbert path presents smoother direction changes and better movement continuity, which allows easier access to certain portions of the route without requiring unnecessary traversal through other areas.
- The Hilbert curve preserves spatial proximity, meaning that the points within each quadrant are traversed consecutively while maintaining the same visitation order for each subdivision.

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- Scalability can be increased or decreased very easily by using mathematical formulas.
- The space is covered in a more balanced and compact manner, without excessive concentration on certain rows or columns.

Differences in which the Snake Path has clear advantages:

- The Snake path is easier to implement, consisting of simple vertical lines connected at the ends.
- It is easier to follow visually.
- It is well suited for small warehouses, where the use of the Hilbert method may not necessarily be justified.
- The method is intuitive.
- Traversal time may be shorter due to the lower number of turns.

Example of traversal time calculation for the example presented above. A distance of 15 units and a speed of 1 unit/s are considered.

$$T = \frac{d}{v} + Nr. turns * T_{turns} + Nr. stops * T_{stops} \quad (1)$$

$$T_{Hilbert} = \frac{15u}{1u/s} + 11 * 1 + 16 * 5 = 15 + 11 + 80 = 106 \text{ s} \quad (2)$$

$$T_{Snake} = \frac{15u}{1u/s} + 6 * 1 + 16 * 5 = 15 + 6 + 80 = 101 \text{ s} \quad (3)$$

In conclusion, both traversal methods present advantages as well as disadvantages. Therefore, if a simple and easy-to-understand algorithm is required, the Snake method would be the preferred choice. On the other hand, if a more complex algorithm with better scalability and improved space coverage is desired, the Hilbert method would be more suitable.

5. Implementation of Hilbert Curve using a C++ program

Within this chapter, a complete C++ program is presented, which takes the algorithm used for generating the Hilbert Curve and optimizes it so that the user can choose to traverse only a specific portion of the entire route, while the program also generates a realistic representation of the obtained path. [5], [6]

```

1  void afisare()
2  {
3      cout << "Punctele sunt: ";
4      for (int i = 0; i < n; i++)
5          cout << p[i] << " ";
6      cout << endl;
7  }
8
9  void citire()
10 {
11     cout << "Introduceti coordonatele punctelor curbei Hilbert (dimensiune grila, coordonata, directia cadrului): ";
12     int m, n, x, y, dir;
13     while (m <= 0 || n <= 0 || x <= 0 || y <= 0 || dir <= 0 || dir >= 3)
14     {
15         cout << "Gresita introducerea datelor. Introduceti din nou: ";
16         m = 0; n = 0; x = 0; y = 0; dir = 0;
17     }
18     p = new int[m * n];
19     for (int i = 0; i < m * n; i++)
20         p[i] = 0;
21 }
22
23 void transformare(int x, int y, int dir)
24 {
25     int m, n, x1, y1, x2, y2, x3, y3, x4, y4, x5, y5, x6, y6, x7, y7, x8, y8, x9, y9, x10, y10, x11, y11, x12, y12, x13, y13, x14, y14, x15, y15, x16, y16, x17, y17, x18, y18, x19, y19, x20, y20, x21, y21, x22, y22, x23, y23, x24, y24, x25, y25, x26, y26, x27, y27, x28, y28, x29, y29, x30, y30, x31, y31, x32, y32, x33, y33, x34, y34, x35, y35, x36, y36, x37, y37, x38, y38, x39, y39, x40, y40, x41, y41, x42, y42, x43, y43, x44, y44, x45, y45, x46, y46, x47, y47, x48, y48, x49, y49, x50, y50, x51, y51, x52, y52, x53, y53, x54, y54, x55, y55, x56, y56, x57, y57, x58, y58, x59, y59, x60, y60, x61, y61, x62, y62, x63, y63, x64, y64, x65, y65, x66, y66, x67, y67, x68, y68, x69, y69, x70, y70, x71, y71, x72, y72, x73, y73, x74, y74, x75, y75, x76, y76, x77, y77, x78, y78, x79, y79, x80, y80, x81, y81, x82, y82, x83, y83, x84, y84, x85, y85, x86, y86, x87, y87, x88, y88, x89, y89, x90, y90, x91, y91, x92, y92, x93, y93, x94, y94, x95, y95, x96, y96, x97, y97, x98, y98, x99, y99, x100, y100, x101, y101, x102, y102, x103, y103, x104, y104, x105, y105, x106, y106, x107, y107, x108, y108, x109, y109, x110, y110, x111, y111, x112, y112, x113, y113, x114, y114, x115, y115, x116, y116, x117, y117, x118, y118, x119, y119, x120, y120, x121, y121, x122, y122, x123, y123, x124, y124, x125, y125, x126, y126, x127, y127, x128, y128, x129, y129, x130, y130, x131, y131, x132, y132, x133, y133, x134, y134, x135, y135, x136, y136, x137, y137, x138, y138, x139, y139, x140, y140, x141, y141, x142, y142, x143, y143, x144, y144, x145, y145, x146, y146, x147, y147, x148, y148, x149, y149, x150, y150, x151, y151, x152, y152, x153, y153, x154, y154, x155, y155, x156, y156, x157, y157, x158, y158, x159, y159, x160, y160, x161, y161, x162, y162, x163, y163, x164, y164, x165, y165, x166, y166, x167, y167, x168, y168, x169, y169, x170, y170, x171, y171, x172, y172, x173, y173, x174, y174, x175, y175, x176, y176, x177, y177, x178, y178, x179, y179, x180, y180, x181, y181, x182, y182, x183, y183, x184, y184, x185, y185, x186, y186, x187, y187, x188, y188, x189, y189, x190, y190, x191, y191, x192, y192, x193, y193, x194, y194, x195, y195, x196, y196, x197, y197, x198, y198, x199, y199, x200, y200, x201, y201, x202, y202, x203, y203, x204, y204, x205, y205, x206, y206, x207, y207, x208, y208, x209, y209, x210, y210, x211, y211, x212, y212, x213, y213, x214, y214, x215, y215, x216, y216, x217, y217, x218, y218, x219, y219, x220, y220, x221, y221, x222, y222, x223, y223, x224, y224, x225, y225, x226, y226, x227, y227, x228, y228, x229, y229, x230, y230, x231, y231, x232, y232, x233, y233, x234, y234, x235, y235, x236, y236, x237, y237, x238, y238, x239, y239, x240, y240, x241, y241, x242, y242, x243, y243, x244, y244, x245, y245, x246, y246, x247, y247, x248, y248, x249, y249, x250, y250, x251, y251, x252, y252, x253, y253, x254, y254, x255, y255, x256, y256, x257, y257, x258, y258, x259, y259, x260, y260, x261, y261, x262, y262, x263, y263, x264, y264, x265, y265, x266, y266, x267, y267, x268, y268, x269, y269, x270, y270, x271, y271, x272, y272, x273, y273, x274, y274, x275, y275, x276, y276, x277, y277, x278, y278, x279, y279, x280, y280, x281, y281, x282, y282, x283, y283, x284, y284, x285, y285, x286, y286, x287, y287, x288, y288, x289, y289, x290, y290, x291, y291, x292, y292, x293, y293, x294, y294, x295, y295, x296, y296, x297, y297, x298, y298, x299, y299, x300, y300, x301, y301, x302, y302, x303, y303, x304, y304, x305, y305, x306, y306, x307, y307, x308, y308, x309, y309, x310, y310, x311, y311, x312, y312, x313, y313, x314, y314, x315, y315, x316, y316, x317, y317, x318, y318, x319, y319, x320, y320, x321, y321, x322, y322, x323, y323, x324, y324, x325, y325, x326, y326, x327, y327, x328, y328, x329, y329, x330, y330, x331, y331, x332, y332, x333, y333, x334, y334, x335, y335, x336, y336, x337, y337, x338, y338, x339, y339, x340, y340, x341, y341, x342, y342, x343, y343, x344, y344, x345, y345, x346, y346, x347, y347, x348, y348, x349, y349, x350, y350, x351, y351, x352, y352, x353, y353, x354, y354, x355, y355, x356, y356, x357, y357, x358, y358, x359, y359, x360, y360, x361, y361, x362, y362, x363, y363, x364, y364, x365, y365, x366, y366, x367, y367, x368, y368, x369, y369, x370, y370, x371, y371, x372, y372, x373, y373, x374, y374, x375, y375, x376, y376, x377, y377, x378, y378, x379, y379, x380, y380, x381, y381, x382, y382, x383, y383, x384, y384, x385, y385, x386, y386, x387, y387, x388, y388, x389, y389, x390, y390, x391, y391, x392, y392, x393, y393, x394, y394, x395, y395, x396, y396, x3
```

In the program presented in Figure 3, several important functions are used, which are necessary for generating the Hilbert path, namely:

- ✓ The `d2xy()` function converts a Hilbert index (`d`) into a pair of coordinates (`x`, `y`). In practice, it determines the position of a point within the grid.

- ✓ The `afiseaza()` function traverses all the points of the curve and displays the corresponding coordinates for each Hilbert index.

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```

263     cout << "Vrei sa vezi traseul in format grafic? (1/0): ";
264     cin >> ok;
265     if (ok == 1)
266         traseu(size, offsetX, offsetY);
267     return;
268 }
269
270
271
272
273     cout << "Nivel Nivel " << nivel << " ==> n";
274     cout << "1 - Afiseaza n";
275     cout << "2 - Coborâ la nivelul urmator n";
276     int alegere;
277     cout << "Alegere: ";
278     cin >> alegere;
279     if (alegere == 1)
280     {
281         afiseaza(size, offsetX, offsetY);
282     }
283     if (alegere == 2)
284     {
285         nivel--;
286         traseu(size, offsetX, offsetY);
287     }
288     return;
289 }
290
291 int main() //Programul principal
292 {
293     int n;
294     cout << "Nivel total n: ";
295     cin >> n;
296     int size = 1 << n; //size-ul este nivelul grilei, care depinde de n, si are formula de 2^n (scris pe biti)
297     explore(n, size, 0, 0);
298     return 0;
299 }

```

Fig. 4. Implementation of Hilbert Curve using a C++ program

- ✓ The traseu_d() function displays a selected portion of the Hilbert curve between two indices chosen by the user and can also graphically represent the path between them.
- ✓ The traseu() function allows the user to choose the starting and ending points, either through coordinates or through Hilbert indices.
- ✓ The explore() function manages navigation between the levels of the fractal. The user can select one of the four quadrants, while the program automatically updates the analyzed area.
- ✓ The main() function represents the starting point of the program. Here, the curve level is introduced, the grid size is calculated, and the explore() function is called.

```

Nivel total n: 2
===== Nivel 2 =====
1 - Afiseaza
2 - Coborâ la nivelul urmator
Alegere: 1
d = 0 -> (0, 0)
d = 1 -> (1, 0)
d = 2 -> (1, 1)
d = 3 -> (0, 1)
d = 4 -> (0, 2)
d = 5 -> (0, 3)
d = 6 -> (1, 3)
d = 7 -> (1, 2)
d = 8 -> (2, 2)
d = 9 -> (2, 3)
d = 10 -> (3, 3)
d = 11 -> (3, 2)
d = 12 -> (3, 1)
d = 13 -> (2, 1)
d = 14 -> (2, 0)
d = 15 -> (3, 0)

Vrei sa vezi traseul in format grafic? (1/0): 1
1 - Coordonate
2 - Indici Hilbert
Optiune: 2

Start d: 0
End d: 15

Traseu pe curba Hilbert:
d = 0 -> (0, 0)
d = 1 -> (1, 0)
d = 2 -> (1, 1)
d = 3 -> (0, 1)
d = 4 -> (0, 2)
d = 5 -> (0, 3)
d = 6 -> (1, 3)
d = 7 -> (1, 2)
d = 8 -> (2, 2)
d = 9 -> (2, 3)
d = 10 -> (3, 3)
d = 11 -> (3, 2)
d = 12 -> (3, 1)
d = 13 -> (2, 1)
d = 14 -> (2, 0)
d = 15 -> (3, 0)

Traseu grafic:
o-o o-o
| | |
| | |
o-o o-o
| |
o-o o-o
| |
o-o o-o

...Program finished with exit code 0
Press ENTER to exit console.

```

Fig. 5. The C++ implementation for generating the Hilbert Curve. Results

The developed program operates as follows: the user initially selects the level of the Hilbert curve (n) and based on this value the size of the grid in which the curve is generated (2^n) is determined. Afterwards, the user can choose to display the Hilbert indices (d) together with the associated coordinates and can also select the graphical representation of the chosen path.

Furthermore, the user has the possibility to recursively explore the lower levels of the

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fractal. If descending to a lower level is selected, the user can choose one of the four quadrants of the fractal structure, while the program automatically updates the grid size and the coordinates corresponding to the newly selected area.

6. Implementation of the QR codes in a Hilbert Curve-Based Path

The implementation of QR codes in such a system, based on the Hilbert fractal curve, can be successfully achieved, especially when the goal is to analyze the traceability of a particular automated system or to use an intelligent database.

Such a QR code may contain essential information about products, such as their exact location, batch number, expiration date, last scanning time, operational status, and other relevant data.

In addition, a heatmap-based diagram could be very useful within a Hilbert-type path, especially when the route is divided into multiple quadrants and each quadrant is accessed by a different automated system (AS/RS, AGV, etc.). Therefore, simply by scanning a QR code located at each point where an automated system operates, human operators would be able to identify exactly which points are more crowded or where operational issues might occur, such as expired products, areas with very high waiting times, problems related to product retrieval, or frequently accessed zones.

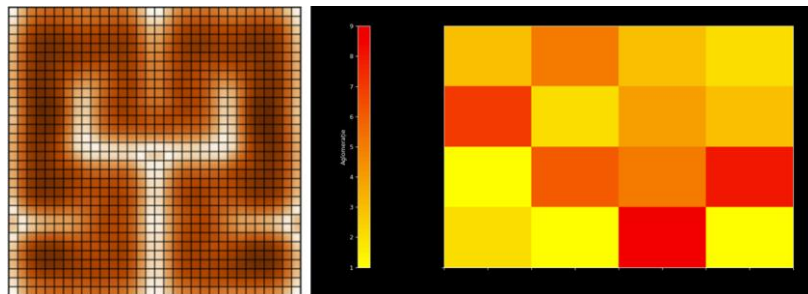


Fig. 6. An example of a heatmap linked to a Hilbert Curve system that can be used in an automated warehouse

The figure above represents a heatmap that may illustrate the congestion level within a logistics warehouse. The 8 rectangles correspond to the 8 points of the Hilbert curve, while 4 adjacent rectangles form one quadrant of the curve.

If the Hilbert-type algorithm were applied within this logistics warehouse, it could be considered a second-order Hilbert curve, which can be divided into 4 equal curves, each having the size of one quadrant. In this scenario, an automated system could scan the QR codes of the products located within its corresponding quadrant, and the product scanning process would generate this heatmap, highlighting the most frequently accessed areas of the warehouse or the zones where delays may occur.

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Thus, if a certain quadrant records a higher number of QR scans within a short period of time, the heatmap may indicate intense activity in that area. This may suggest, for example, a high demand for certain products, long waiting times, or the need to redistribute the logistics flow.

In the figure above, it can be clearly observed that there is a significant concentration of products in the fourth quadrant, suggesting that urgent intervention or the addition of a second automated system may be necessary in order to reduce congestion in that area.

AMR/AGV → QR Code Scan → Data Base → Generation of the Heatmap → Future Optimization

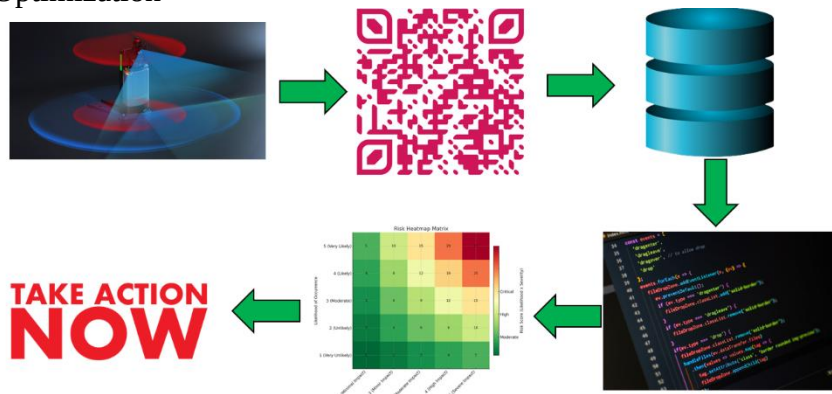


Fig. 7. An example of an automated system that uses QR codes and Heatmaps

7. Conclusions

Within this paper, different movement methods used in logistics warehouses were presented, such as the method inspired by the Hilbert curve and the Snake-type movement method. These two movement methods were compared with each other, while also highlighting their differences compared to the graph-based method. In addition, the Hilbert fractal method was analyzed in greater detail through a C++ program capable of calculating the fractal path and generating a graphical representation of the type of route selected by the user.

Finally, a possible implementation of QR codes within such a warehouse environment was also discussed, in which a Hilbert-based algorithm is already implemented and can be scaled and divided into multiple quadrants, each of them being autonomous and requiring its own operational analysis.

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STUDY ON THE COMBINER gd mc1-v VOYAGER EQUIPMENT AND METHODS FOR OPERATIONAL OPTIMIZATION

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ABSTRACT: This study presents a case analysis of the GD MC1-V Voyager Combiner used in the manufacturing process of heated tobacco products, emphasizing its functional role and optimization potential within an industrial production line. The research focuses on the performance of optical inspection systems responsible for detecting the position of the metallic strip inside the tobacco rod. A detailed evaluation of rejection data revealed a high proportion of false – positive rejects generated by a specific vision camera. Targeted electronic parameter adjustments and mechanical improvements to the lighting conditions were implemented. As a result, rejection rates were significantly reduced, process stability was improved, and manual operational cost savings of approximately 75.000 Euro were achieved.

KEY WORDS: Manufacturing efficiency, Operational optimization, PMI, Vision cameras

1. Introduction

The heated tobacco industry has developed based on the heat-not-burn principle, which involves heating tobacco at temperatures below combustion, with the aim of avoiding its burning, a process responsible for generating most of the toxic substances found in cigarette smoke. Through this approach, heated tobacco products occupy a distinct position within the tobacco and nicotine product market, being mainly addressed to adult smokers who cannot completely give up consumption [1], [7].

From a technological point of view, heat-not-burn products use electronic devices that heat processed tobacco, producing an aerosol that contains nicotine, but without smoke and ash. The specialized literature and data reported by manufacturers indicate a significant reduction in the levels of certain harmful chemical substances compared with traditional cigarettes, although these products are not risk-free and maintain nicotine addiction. In this context, the heated tobacco industry is positioned at the intersection of technological innovation, the commercial strategies of major companies in the field, and scientific debates regarding the potential role of these products in reducing the risks associated with smoking [1], [6], [7].

At European and national level, heated tobacco is integrated into a regulatory framework specific to “new” tobacco products, being subject to strict requirements regarding notification, labeling, and commercialization. The rapid development of this segment reflects not only the industry’s adaptation to legislative and social changes, but also the increasing role that alternative products may have in the future structure of the tobacco market [2], [8].

The present paper aims to highlight the position occupied by Philip Morris International factories within the heated tobacco industry, analyzed both from the perspective of the product portfolio and through a case study applied to the equipment used in the cigarette forming process, namely the Combiner GD MC1-V Voyager, mentioned in the title of the paper. At the same time, this study represents a continuation of the scientific research approach initiated in the previous paper, in which the manufacturing process of products based on tobacco heating technology was presented at a general level, from the receipt of raw material (tobacco leaves) to packaging and compliance with legal requirements in order to be distributed to consumers.

2. PMI positioning compared with competitors and the dynamics of the heated tobacco market

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Philip Morris International (PMI) holds a dominant global position in the heated tobacco products industry, a position supported mainly by the performance of the IQOS brand. According to estimates made by *TobaccoIntelligence*, IQOS accounts for approximately 75% of the global heat-not-burn product market volume, placing PMI significantly ahead of all direct competitors [3], [9].

The main competitors, British American Tobacco (BAT) and Japan Tobacco International (JTI), occupy secondary positions, with BAT (GLO) having an estimated share between 10–15%, while JTI (Ploom) has a global share between 5–10%, with a predominant concentration on the Japanese market. This significant difference in shares highlights a high degree of market concentration, in which PMI acts as the main leader in this field [3].

At the same time, this position is also indirectly confirmed by the financial data reported by the company, which indicates that smoke-free products, dominated by IQOS, generate over 40% of PMI's total revenues, with the heat-not-burn category representing the company's main growth driver at global level [4], [9].

The evolution of the heated tobacco products market supports this favorable positioning. The report published by *Grand View Research* highlights, through the market analysis chart (Fig. 1. Market analysis of heated tobacco-based products), an accelerated and clearly visible increase in the value of the global market, which reached approximately USD 49.1 billion in 2024. Also, the upward trajectory shown in the chart indicates the rapid expansion of the segment, driven by increasingly strict restrictions applied to conventional cigarettes, by changes in adult consumer preferences, and by the strategic investments made by industry leaders [5].

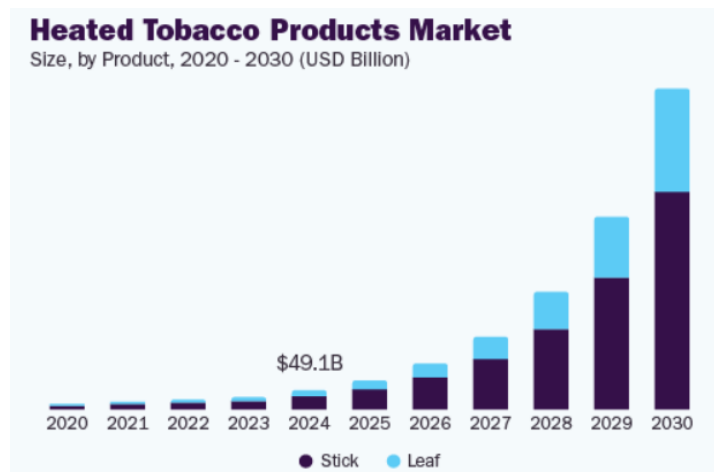


Fig. 1. Market analysis of heated tobacco-based products [5]

Therefore, it can be stated that the future of digitalization and automation of industrial processes remains favorable, given that organizations aim to increase operational efficiency, optimize production flows, and use available resources as efficiently as possible. In a context where higher volumes and performance are desired with limited resources, automation solutions contribute to reducing operational costs, decreasing errors generated by human intervention, and carrying out activities more rapidly.

Following the aspects presented above, the analysis will focus on the Combiner GD MC1-V Voyager equipment, through the practical identification and evaluation of optimization solutions for its operating mode, with the main objective of reducing the number of nonconforming products resulting from the process, as well as increasing the overall productivity of the equipment.

3. The functional role of the equipment within the production flow of heated tobacco cigarettes

The GD MC1-Voyager Combiner brings together, within an integrated technological flow, all types of semi-finished sticks required to obtain the double heat stick, using both

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flavored and non-flavored components, in accordance with the specific requirements of the manufacturing process. The technological line processes the CLT tobacco stick, which includes a metallic susceptor in its structure, together with the T-HAT, HAT, FP, and MPF sticks, which contribute to the final configuration of the product. These semi-finished products are transported by compressed air from the forming machines to the receivers, which take them over and subsequently introduce them into the dedicated functional modules of the equipment, presented later in the next chapter. Within the process, semi-composite stick paper is used as wrapping material for the component structure, while tipping paper ensures the formation of the double stick.

At the end of the forming process, the double sticks are automatically transferred to the cutting equipment and then to the packaging line, where the packs are formed successively, the cigarettes are inserted into the packs, the cartons are formed, the packs are loaded into cartons, and finally the cartons are inserted into cases.

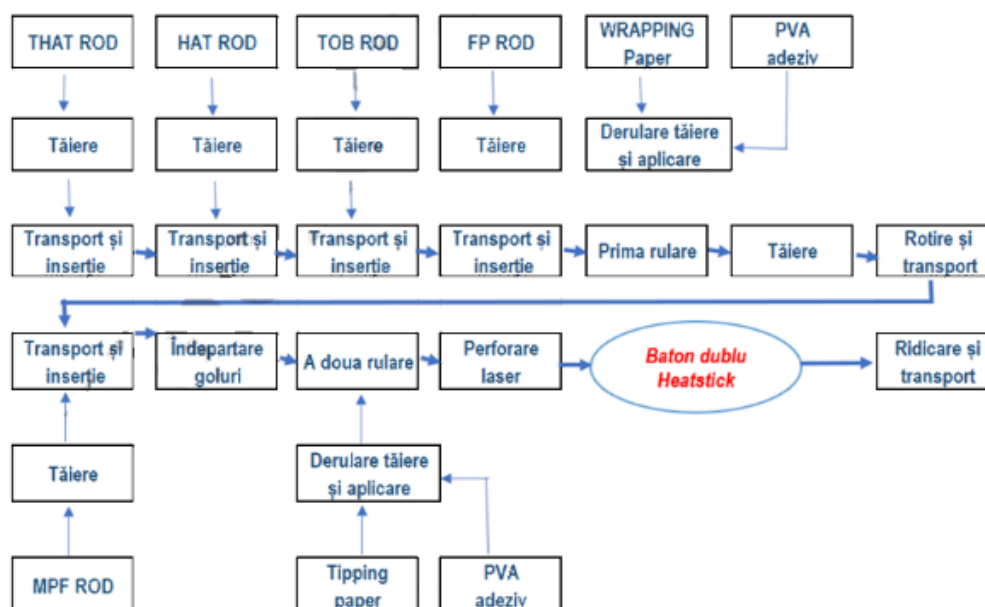


Fig. 2. Technological process for producing the double stick

4. Operational functioning of the Combiner GD MC1-V Voyager equipment

The T-HAT (*Thin Hollow Acetate Tube*) and HAT (*Hollow Acetate Tube*) semi-finished sticks, corresponding to sections G2 and G3, are fed from external shooter-type units, being taken over by the feeding system called *filter receiver* and subsequently directed to the main hopper of the equipment.

The CLT (*Cast Leaf Tobacco*) tobacco sticks, corresponding to section G4, are supplied by an external *filter elevator* unit and transported by means of a conveyor belt to the hopper, from where they are transferred into a mini-hopper with adjustable capacity. The resulting composite segments are extracted from the transport drum by the separation drum and transferred to the pitch-changing drum of the next module. The transfer module, corresponding to section C1, is equipped with two optical inspection cameras, which monitor the internal geometry of the product in real time, with the objective of verifying the positioning of the tobacco stick inside the semi-composite structure, as well as performing additional checks regarding the presence and position of the metallic susceptor.

In parallel, the FP (*Front Plug*) and MPF (*Mouthpiece Filter*) semi-finished sticks are

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fed through external shooter-type units, being taken over by the same *filter receiver* system, according to an identical dispatching and receiving process also used for the T-HAT and HAT sticks, and directed to the dedicated hoppers. The semi-composite stick wrapping paper, corresponding to section R1 and supplied by the external RF20 unit, is pneumatically transported to the equipment, where it is unwound, tensioned, and temporarily stored as a reserve by means of a pneumatic system. To obtain the *double stick* configuration, the tipping paper, corresponding to section R2, is fed from an external unit, passes through the pulling roller, and is subsequently guided to the corrugator, the pre-unwinding rollers, and the driven roller, which ensures retroactive adjustment of the material tension.

The double sticks obtained are successively transported between the guide drums and directed to the laser perforation drum, corresponding to section L1, where perforation is performed by controlled burning of the paper, using a laser beam focused on the outer surface of the filter, in the T-HAT segment area. This stage leads to obtaining ventilated double sticks. The laser beam, generated by the dedicated source, is directed to the optical perforation head through a system of mirrors and lenses, while the synchronization of the head movement with the transport drum allows the repeated and precise execution of the perforations.

The following chapter focuses on the filter-combiner module of the equipment, respectively on the C1 transfer section, with emphasis on the optical inspection area dedicated to detecting and analyzing the internal structure of the semi-composite stick. The analysis mainly targets the operation of detection systems based on a set of 4 cameras, used to monitor the positioning of the CLT stick inside the semi-composite structure.

5. Presentation of equipment optimization opportunities for reducing rejects and associated costs

As previously mentioned, in the continuation of the paper, attention is directed toward the transfer area of the equipment, respectively toward the MS-VIU optical inspection systems. The role of these cameras is to identify the presence and positioning of the metallic strip inside the tobacco stick.



Fig. 3. Optical inspection area – location within the equipment

Based on the rejection reasons associated with this group of cameras, a detailed analysis of optimization opportunities was carried out. This was based both on the high level of rejects generated during equipment operation and on the significant economic impact of the resulting losses.

The analysis aimed to identify the main causes contributing to the generation of rejections, as well as to evaluate the process and inspection parameters that can be adjusted in order to improve system performance.

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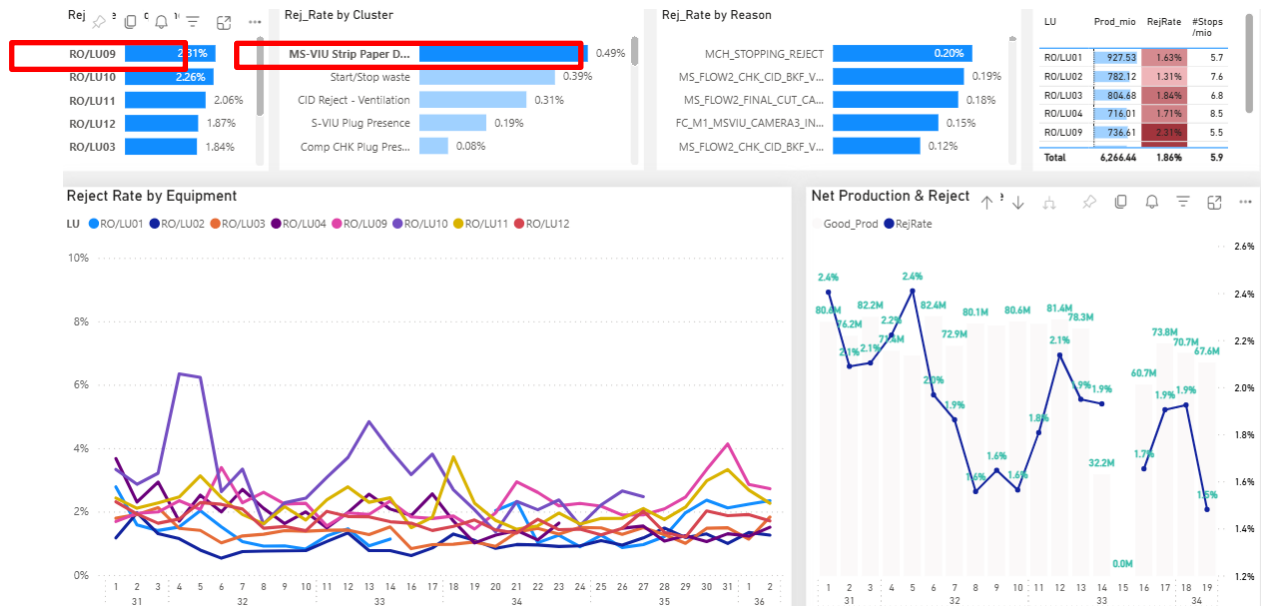


Fig. 4. Chart associated with the rejections generated by the Combiner GD MC1-V Voyager equipment

The decision to focus was based on a structured analysis of the rejection causes, carried out in stages, starting with the identification of the main reasons generating losses in the process. Following this evaluation, visible in Fig. 5. *Analysis performed according to rejection reasons*, the reason “Invalid Strip Paper Distance” was highlighted as one of the major contributors to the total rejection rate of the equipment. This type of defect is associated with improper positioning of the metallic strip in relation to the outer edge of the tobacco stick, indicating a deviation of the internal structure of the semi-composite stick from the accepted parameters.

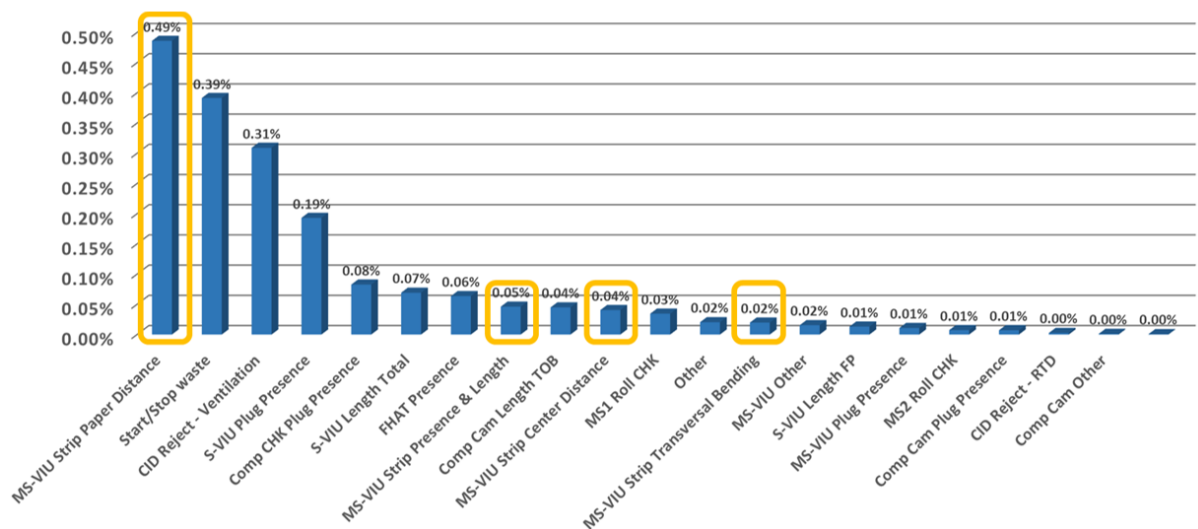


Fig. 5. Analysis performed according to rejection reasons

Subsequently, the analysis was extended to the level of the production lines and the related detection systems, in order to determine the production area/line with the highest impact. The results showed that the highest rejection percentage associated with the previously identified reason is found within production line number 9 (Figure 6).

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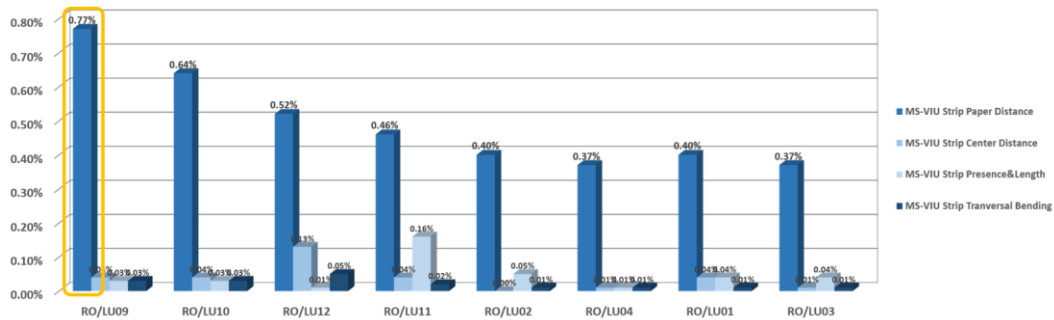


Fig. 6. Analysis performed according to rejection reasons associated with the production lines

Starting from these preliminary results, the analysis is deepened by focusing on the specific component identified as responsible, namely the inspection camera. The adopted approach involves concentrating on a single control point, with the aim of clearly defining its influence on the overall performance of the system.

This focus allows a detailed investigation of the operating parameters and associated operational conditions, facilitating the definition of targeted and well-founded corrective actions. At the same time, the approach reduces the complexity of the analysis by eliminating multiple variables and allowing a more precise evaluation of the impact of each implemented measure.

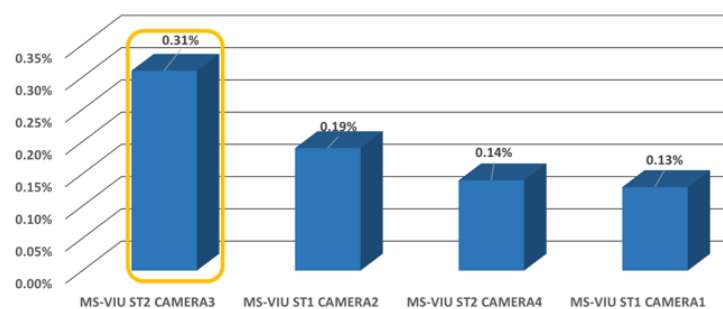


Fig. 7. Analysis performed at the level of the detection systems recording the highest percentage of rejections due to the “Invalid Strip Paper Distance” reason

After identifying the camera responsible for the highest percentage of rejections, a systematic analysis process was initiated, oriented toward identifying opportunities to optimize its performance. This stage included a detailed evaluation of the operating mode, configuration parameters, and operational conditions that may influence detection accuracy. All of these were carried out using the “5 Why” method, based on repeated “Why?” questions in order to reach the root cause of the problem, not only its symptom.

Following the investigations carried out, it was highlighted that approximately 21.5% of the total rejections generated by this system were classified as false positives, based on a sample of 200 sticks. This result indicates a high sensitivity of the inspection system in relation to process or material variations, leading to the erroneous identification of conforming products as nonconforming.

STUDY ON THE COMBINER gd mc1-v VOYAGER EQUIPMENT AND METHODS FOR OPERATIONAL OPTIMIZATION

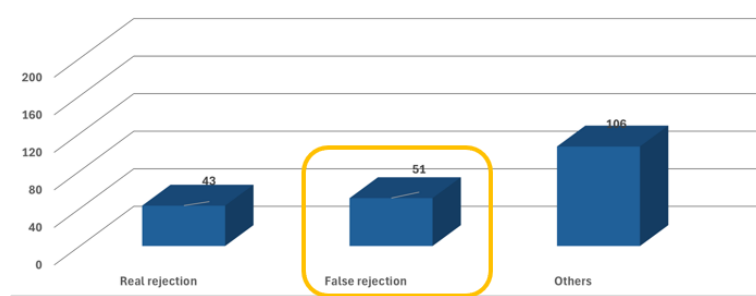


Fig. 8. Analysis performed at the level of real and false rejection reasons

A false rejection refers to the situation in which the metallic strip is correctly positioned and compliant with specifications inside the tobacco stick, but the optical inspection system cannot detect it properly, leading to the generation of erroneous rejections and implicitly to an increase in the operational costs associated with equipment operation. In the images presented below, the detection area of the analyzed camera is illustrated, while also highlighting the way in which the stick is identified and framed by the visual system through a rectangular region of interest used to evaluate the positional conformity of the metallic strip.

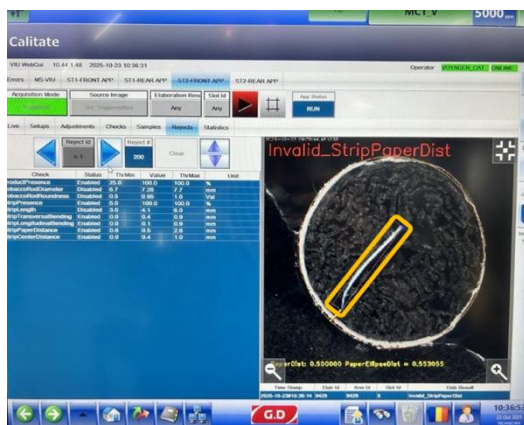


Fig. 9. Real detection image of the metallic strip position inside the stick.

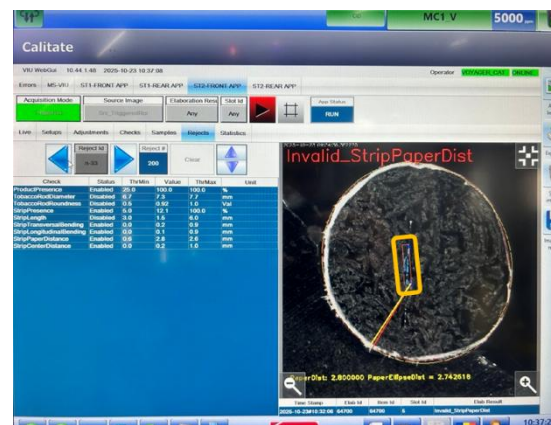


Fig. 10. Erroneous/false detection image of the metallic strip position inside the stick.

To reduce the number of rejections associated with the visual inspection system, a series of adjustments were investigated and applied both at the electronic level and at the mechanical level of the camera.

Regarding the electronic adjustments, the analysis focused on the specific image acquisition parameters, namely *camera gain*, *camera exposure time*, and *pixel size*. The *camera gain* parameter represents a multiplicative amplification factor of the signal captured by the sensor and is used in situations where the exposure time and LED current settings are not sufficient to obtain the desired image brightness level; at the same time, increasing this parameter also leads to the amplification of image noise, an aspect that may influence detection accuracy. The exposure time (*camera exposure time*) defines the time interval during which the camera sensor captures light, having a direct impact on the amount of optical information recorded and on the clarity of the resulting image. The pixel size (*pixel size*), expressed in millimeters, is used to convert units from pixels into real dimensions.

Complementary to the electronic adjustments, at mechanical level an improvement of the lighting conditions was implemented by installing an additional light source in the camera detection area, with the aim of increasing image contrast and improving the camera's ability to correctly identify the position of the metallic strip inside the tobacco stick.

STUDY ON THE COMBINER gd mc1-v VOYAGER EQUIPMENT AND METHODS FOR OPERATIONAL OPTIMIZATION

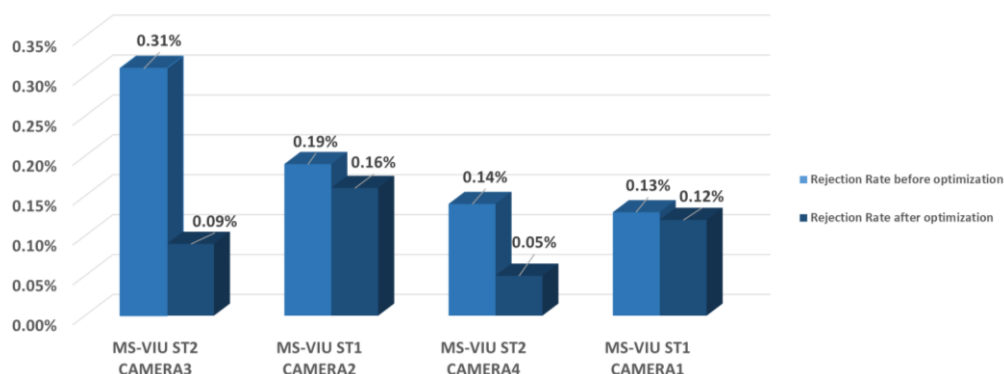


Fig. 11. Analysis performed at the level of rejection reasons after implementing the improvements

A false rejection refers to the situation in which the metallic strip is correctly positioned and compliant with specifications inside the tobacco stick, but the optical inspection system cannot detect it properly, leading to the generation of erroneous rejections and implicitly to an increase in the operational costs associated with equipment operation. In the images presented below, the detection area of the analyzed camera is illustrated, while also highlighting the way in which the stick is identified and framed by the visual system through a rectangular region of interest used to evaluate the positional conformity of the metallic strip.

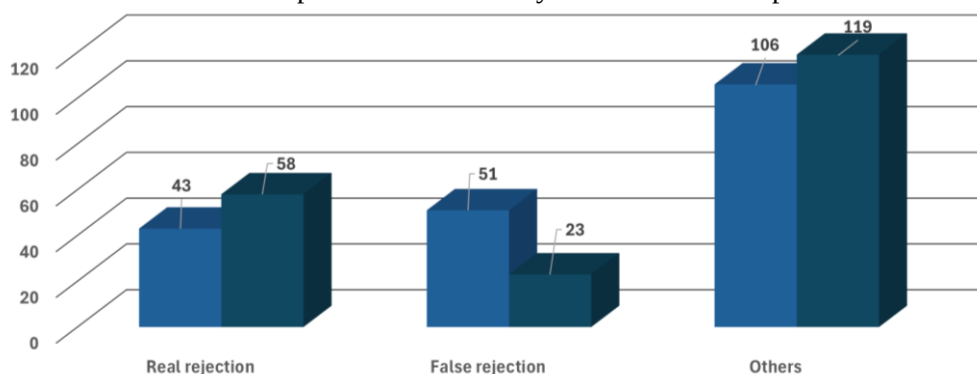


Fig. 12. Analysis performed at the level of real and false rejection reasons after implementing the improvements

6. Conclusions

In conclusion, the results obtained clearly highlight the effectiveness of the implemented measures, demonstrating a direct and measurable impact on process performance. The improvements made reflect an effective optimization of the relationship between the sensitivity of the detection system and the accuracy of identifying real defects, contributing to increased reliability and stability of the inspection.

From an economic point of view, these results translate into a concrete and quantifiable benefit, estimated at a current saving of approximately 75,000 euros. This value confirms once again the relevance and effectiveness of the applied interventions, supporting the need to maintain and extend this type of approach within continuous optimization processes.

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Planning the implementation of RPA TECHNOLOGY IN AN ORGANIZATION USING MICROSOFT PROJECT

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***ABSTRACT:** This paper focuses on the implementation of Robotic Process Automation (RPA) technology within an organization, where it plays an important role in automating and optimizing logistics processes, as improving workflow efficiency directly influences operational performance. The central element of this paper is the use of Microsoft Project as the main project planning and management tool, facilitating the clear structuring of project phases, task organization, the establishment of dependency relationships between them, and the efficient allocation of resources. At the same time, this tool enabled a detailed visualization of the entire project and continuous progress monitoring. Therefore, this paper highlights the importance of using Microsoft Project in the management of automation projects.*

***KEYWORDS:** Robotic Process Automation (RPA), logistics processes, process automation, Microsoft Project, project management.*

1. Introduction

In the current context of digital transformation, organizations are increasingly focused on identifying effective solutions to optimize operational processes and enhance competitiveness. Business process automation represents one of the main development directions, contributing to the decrease of operational costs, increased productivity, and the minimization of human errors.

The impact of these transformations is clearly reflected in logistics activities, which play an essential role in ensuring operational efficiency and increasing customer satisfaction. Logistics involves managing the flow of goods, information and resources, from procurement to final delivery to the customer, which is a complex process that requires precise coordination and high accuracy [1]. For this reason, the automation of logistics processes is becoming more important, as it enables the optimization of repetitive tasks, reduces errors, and decreases reliance on human intervention. Thus, *Robotic Process Automation* (RPA) technology has emerged as a modern solution for automating repetitive and rule-based tasks, being increasingly used in various industries [2]. By implementing this technology, organizations can improve the efficiency of time-consuming activities and enable employees to focus on higher value-added tasks [2].

Moreover, the implementation of this technology within an organization does not represent only a technological initiative, but a complex process of operational transformation that requires rigorous planning, a detailed analysis of existing processes, and efficient coordination of the involved resources. In this sense, the success of implementation directly depends on how the project planning is developed, on the definition of implementation phases and tasks, required resources, and execution deadlines.

This paper aims to approach the RPA technology implementation process from a project management perspective, using *Microsoft Project* as the main tool for planning, organizing and monitoring tasks. The choice of this software is justified by its ability to support detailed project planning, efficient resource allocation and real-time progress tracking.

2. Current stage of RPA technology implementation and market evolution

Currently, the RPA technology market is developing at a rapid pace, driven by fast technological advancements and the increasing implementation of automation solutions across various sectors [2]. Globally, companies recognize the need to optimize their operations, increase efficiency and reduce costs in order to remain competitive in today's business environment. In this context, RPA is considered an innovative technology capable of supporting organizations in achieving these objectives

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by automating repetitive tasks and streamlining operational processes [3].

According to the study conducted by Precedence Research, the global RPA market size is estimated at 35.27 billion USD in 2026 and is expected to grow to approximately 247.34 billion USD by 2035 (Fig. 1.), registering a compound annual growth rate (CAGR) of 24.20% over the forecast period [3]. This growth is driven by the increasing integration of automation across various industries to improve business process efficiency and enhance operational performance. In addition, the need to reduce operational costs and increase productivity is driving the demand for RPA solutions [3].

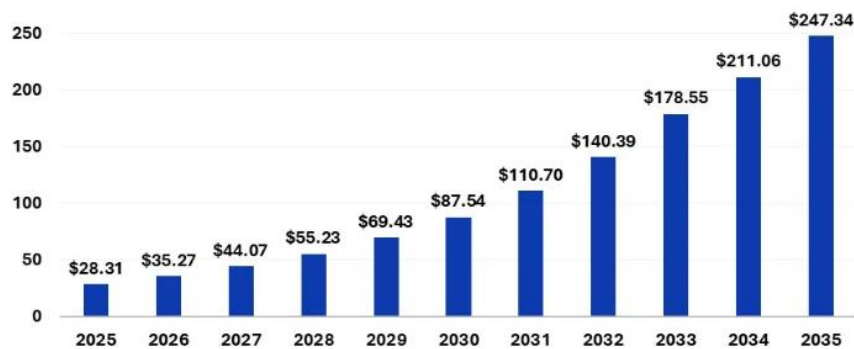


Fig. 1. RPA market evolution (in billion USD) over the period 2026 – 2035 [3]

Considering the RPA market situation by region (Fig. 2.), North America dominates the global market with a share of 38.92% [3]. This is due to the fact that in this region, companies are rapidly adopting RPA technology, investing in automation and having a workforce familiar with digital solutions, which leads to increased competitiveness of companies and, at the same time, generating employment opportunities in other sectors. According to data provided by the *Association for Advancing Automation*, since 2010 more than 180 thousand software robots have been implemented across various American companies, contributing to the creation of over 1.2 million new jobs in the manufacturing sector [3].

Europe ranks second globally, with a market share of 27.95%. This development is mainly driven by the need to reduce high labor costs, reduce human errors and accelerate the processing of operational tasks.

The Asia – Pacific region holds the third position with a market share of 24.72% and is expected to record the fastest growth over the period 2025 – 2034. The rapid growth in this region is driven by the increasing implementation of RPA technology in the pharmaceutical, retail, and manufacturing industries [3]. Also, the increasing awareness of the benefits of RPA technology among various industries and small and medium-sized enterprises is contributing to the expansion of the market in the region [3].

Latin America, along with the Middle East and Africa (MEA), hold the lowest shares of 5.44% and 2.97%.

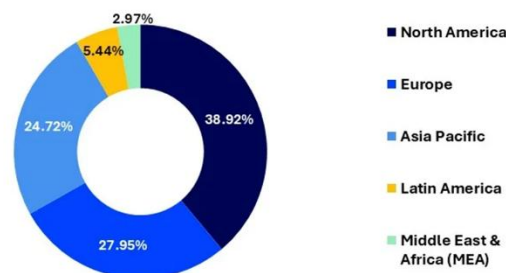


Fig. 2. RPA market share by region (%) [3]

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Therefore, we can say that the future of RPA automation remains promising, as companies aim to increase productivity, accelerate workflows, and reduce expenses [4]. As organizations seek to achieve more with fewer resources, RPA technology contributes to lowering operational costs, reducing human errors, and enabling faster execution of tasks without the need to hire or allocate additional staff.

3. Project purpose and objectives

The purpose of the project is to implement RPA technology within an organization, using the *Microsoft Project* tool, to automate repetitive and time-consuming computer-based processes, in order to increase operational efficiency, reduce execution time, and minimize human errors.

In order to achieve the proposed purpose, the following specific objectives were established:

- Identifying at least 3 processes that can be automated, within 3 weeks from the project launch.
- Evaluating at least 3 RPA solutions available on the market and selecting the right solution within a maximum of 7 weeks from the project initiation.
- Developing and testing at least 3 software robots that reduce processing time by at least 50% and the error rate by 80%, within approximately 8 weeks.
- Implementing RPA technology in the organization, within a maximum of 11 weeks from the approval of the solution.
- Organizing at least 2 training sessions for user instruction.
- Monitoring the performance of the software robots for 3 months after implementation, focusing on time savings and the minimization of errors.

The established objectives form the basis for structuring the project plan and will be converted into tasks, durations, and dependencies within the *Microsoft Project* application. By clearly defining these objectives, an efficient planning process for the implementation of RPA technology is ensured, facilitating progress monitoring and compliance with the established deadlines.

4. Project implementation methodology

The implementation of RPA technology within an organization requires a structured project management approach, considering the complexity of the processes involved and the need for rigorous task planning. In this context, the methodology used in this project is based on the principles of project management, namely the clear definition of phases, the establishment of tasks, resource allocation, duration estimation, and the identification of dependencies between tasks.

The adopted approach is a sequential one, specific to technology implementation projects, in which each phase must be completed before moving on to the next. This structure allows a better risk control, progress monitoring, and compliance with the established deadlines.

For the planning and organization of the project tasks, the *Microsoft Project* tool was used, a specialized project management software that allows the definition, structuring, and monitoring of tasks in an efficient manner [5]. Additionally, it facilitates the graphical representation of the project plan in the form of a Gantt chart, providing a clear overview of task durations, dependency relationships between them, and the overall progress of the project [5].

Microsoft Project also enables the allocation of resources to each task, the estimation of execution durations, and the identification of potential overlaps or conflicts within the planning process [5]. By using this tool, the RPA technology implementation project can be managed in a structured, transparent, and easily updatable manner throughout its execution.

Therefore, the implementation of RPA technology within the organization was planned using the *Microsoft Project* application by structuring the tasks into phases, establishing execution durations, defining dependencies between tasks, and allocating the necessary resources. In this context, the project was divided into several main phases, as follows:

The first phase, **project initiation**, has a duration of one week and includes tasks such as defining the project purpose and objectives, forming the project team, and approving the budget. This phase is essential for establishing the general framework for the project execution.

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The second phase, **process analysis**, lasts three weeks and involves identifying repetitive and time-consuming processes, collecting and documenting information regarding existing processes, and classifying them according to complexity and data volume. Finally, the processes to be automated are selected.

The third phase, **RPA solutions analysis**, has a duration of three weeks and includes tasks such as identifying solution providers, documenting their characteristics, conducting a comparative analysis, and selecting the optimal solution for implementation.

The software robot design and development phase represents the most complex component of the project, with a duration of eight weeks. This phase includes tasks related to structuring workflows, designing the software robots, developing them, and testing them in various scenarios to ensure their correct and efficient operation.

Furthermore, the phase of **implementing RPA technology within the organization**, with a duration of three weeks, involves tasks such as installing the RPA platform, integrating the software robots into the workflows, verifying their functionality, and optimizing their performance.

The user training phase, carried out over the course of one week, involves developing user guides, preparing training materials, and organizing training sessions in order to ensure the efficient use of the implemented solution.

The final phase, **post-implementation monitoring**, takes place over a period of three months and aims to evaluate the performance of the software robots. This phase includes tasks such as monitoring key performance indicators (KPI), collecting user feedback, preparing reports, and identifying improvement opportunities.

The planning of the project tasks was conducted and graphically represented using the Gantt chart, specific to the *Microsoft Project* application. This provides an overall view of the entire project, highlighting the duration of each task, the sequence of phases, and the dependency relationships between them. Additionally, this representation facilitates the identification of potential delays and allows the monitoring of project progress in relation to the established deadlines.

Within the project planning process, the allocation of the necessary resources for the tasks was also performed. These were defined according to type (Fig. 3.), as follows:

- **Work resources:** include human resources and equipment that consume time in order to achieve the objective of a task [6]. This category includes the project manager, responsible for coordinating and monitoring the tasks, the financial and accounting manager, the RPA consultant, the process analyst, the RPA solution developer, the IT specialist, the trainer, and employees, as well as the laptop and the projector.
- **Material resources:** include consumable or usable resources required for the execution of tasks, for which a unit cost is specified [6]. This category includes the RPA platform user manual.
- **Cost resources:** used to highlight the expenses associated with certain tasks [6]. Within the project, such a resource is the training room, required for conducting the training sessions.

	Resource Name	Type	Material	Initials	Group	Max.	Std. Rate	Ovt. Rate	Cost/Use	Accrue	Base	Code	Add New Column
1	Project Manager	Work		PM		400%	100.00 RON/hr	60.00 RON/hr	0.00 RON	Prorated	Calendar		
2	Laptop	Work		L		400%	750.00 RON/yr	0.00 RON/hr	0.00 RON	Prorated	Calendar		
3	Financial and Accounting Manager	Work		FAM		150%	110.00 RON/hr	70.00 RON/hr	0.00 RON	Prorated	Calendar		
4	RPA Consultant	Work		RPA Cons.		100%	125.00 RON/hr	80.00 RON/hr	0.00 RON	Prorated	Calendar		
5	Process Analyst	Work		PA		200%	80.00 RON/hr	50.00 RON/hr	0.00 RON	Prorated	Calendar		
6	RPA Solution Developer	Work		RPA Dev.		250%	110.00 RON/hr	75.00 RON/hr	0.00 RON	Prorated	Calendar		
7	IT Specialist	Work		IT Spec.		100%	80.00 RON/hr	50.00 RON/hr	0.00 RON	Prorated	Calendar		
8	Trainer	Work		T		105%	85.00 RON/hr	55.00 RON/hr	0.00 RON	Prorated	Calendar		
9	RPA Platform User Manual	Material	pcs.	RPA UM			30.00 RON		0.00 RON	Prorated			
10	Employees	Work		E		200%	50.00 RON/hr	25.00 RON/hr	0.00 RON	Prorated	Calendar		
11	Training Room	Cost		TR						Prorated			
12	Projector	Work		P		100%	300.00 RON/yr	0.00 RON/hr	0.00 RON	Prorated	Calendar		

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Fig. 3. Definition of the resources required for executing the tasks

This classification allowed a coherent organization of the resources and an effective alignment of them with the project tasks.

The figures below present the overall structure of the project developed in *Microsoft Project*, highlighting the previously mentioned phases and tasks, the dependency relationships between them, the estimated durations, and the allocation of resources, along with the corresponding Gantt chart of the project.

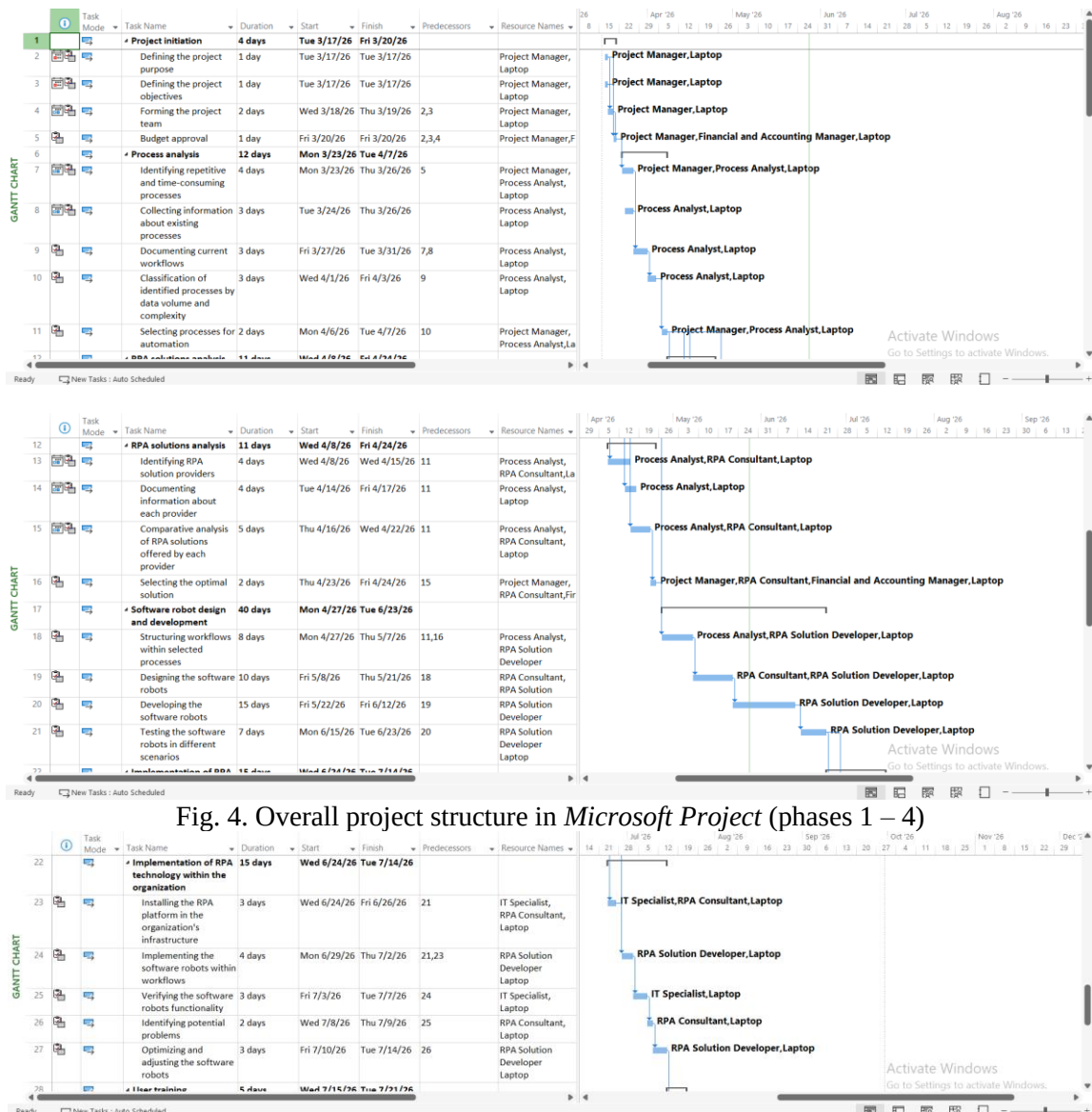


Fig. 4. Overall project structure in *Microsoft Project* (phases 1 – 4)

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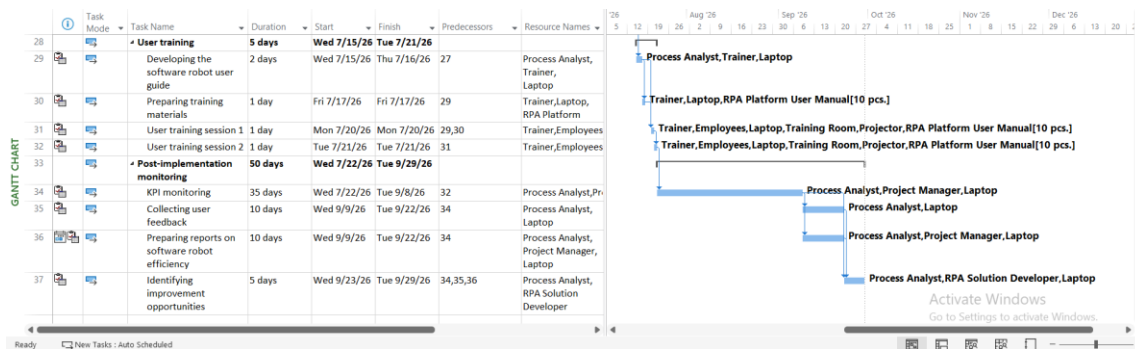


Fig. 5. Overall project structure in *Microsoft Project* (phases 5 – 7)

5. Project monitoring reports

Project monitoring reports are essential tools for tracking and evaluating its progress, providing an overview of the status of tasks, resource utilization, and adherence to the established budget [7]. Through the *Microsoft Project*, these reports are automatically generated based on the entered data, facilitating the analysis of project performance and the identification of potential deviations from the initial plan.

Some relevant project monitoring reports are presented below:

- **Cost overview** (Fig. 6.): provides an overall view of the total project costs, including estimated costs, remaining costs, and project progress [8]. According to the generated report, the total estimated cost of the project is 192909.42 RON, a value equivalent to the remaining cost, indicating that the project has not yet been initiated and no actual expenses have been recorded. At the same time, the report also highlights the distribution of costs across the project phases.

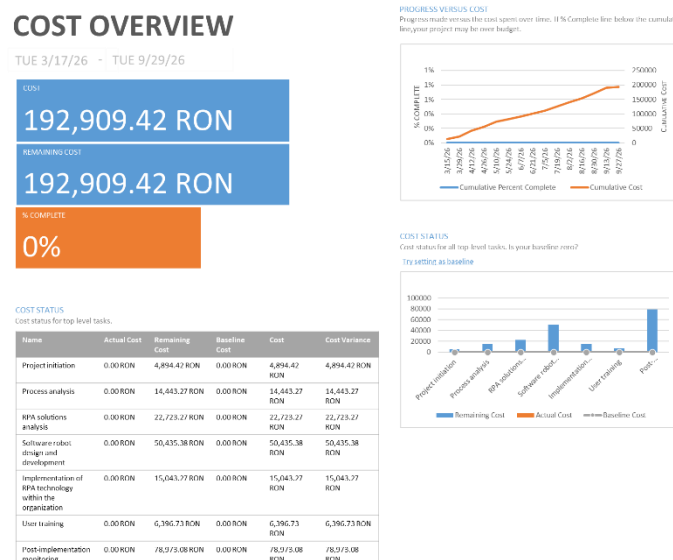


Fig. 6. Cost overview report

- **Resource overview** (Fig. 7.): presents the allocation and utilization of resources within the project, highlighting the workload level of each resource and the associated volume of work [8]. In the case of this project, an uneven distribution of work can be observed, with certain resources showing a higher level of utilization, such as the laptop and the process analyst, which reflects their important role in the implementation of RPA technology.

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RESOURCE OVERVIEW

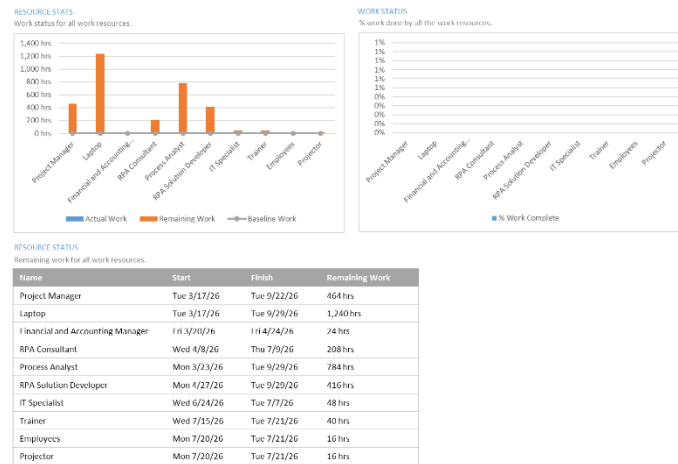


Fig. 7. Resource overview report

- **Resource cost overview** (Fig. 8.): highlights the costs associated with each resource used within the project and their contribution to the total cost [8]. The presented data shows that the highest costs are generated by the resources directly involved in process analysis and development, such as the process analyst, the RPA solution developer, and the project manager, which is justified by the complexity of the tasks performed. Furthermore, the report indicates that most costs are attributed to *work resources*, while *material* and *cost resources* have a reduced contribution to the total project cost.

RESOURCE COST OVERVIEW

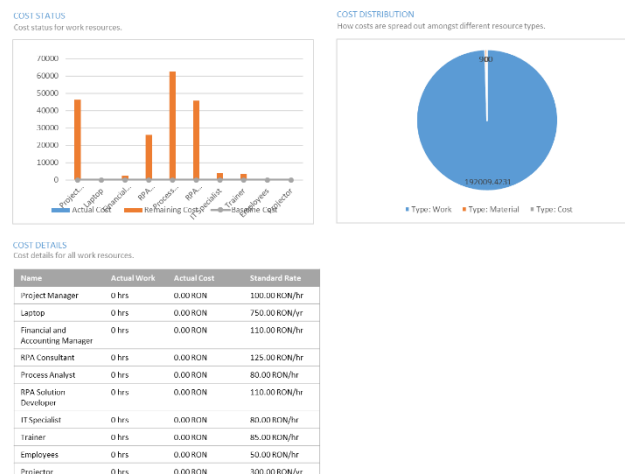


Fig. 8. Resource cost overview report

- **Work overview** (Fig. 9.): presents the total work volume associated with the project, highlighting the completed work, remaining work, and the overall progress of the tasks [8]. According to the report, the total work volume of the project is 3256 hours, entirely allocated as remaining work, indicating that the project has not yet been initiated.

Planning the implementation of RPA TECHNOLOGY IN AN ORGANIZATION USING MICROSOFT PROJECT



Fig. 9. Work overview report

Overall, these reports provide a clear overview of the project planning from the perspective of costs, resources, and work volume, while also enabling effective tracking of its progress and supporting decision-making based on objective data.

6. Final conclusions

The use of *Microsoft Project* played an essential role in achieving a coherent and well-structured planning process for the implementation of RPA technology, providing support in organizing project phases and tasks, setting durations, and efficiently allocating resources. Through its functionalities, such as the Gantt chart and automatic report generation, it was possible to obtain a clear visualization of the entire project, the relationships between tasks, and overall progress, which contributed to a better understanding and control of its execution. Thus, *Microsoft Project* proved to be an indispensable tool in project management, ensuring rigorous planning, effective monitoring, and optimal coordination of all resources involved in the implementation process.

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Extended Reality APPLIED in the Logistics Field

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ABSTRACT: This paper explores the applicability of Virtual Reality (VR) technology in the field of industrial logistics, with a special emphasis on the development of software solutions using the Unity engine. In the context of the transition to Industry 4.0, traditional planning and training methods are becoming insufficient. The paper proposes and analyses two main directions for VR implementation: the creation of "Digital Twins" for optimizing the layout of factories and warehouses, and the development of immersive simulators for training operators in complex or hazardous scenarios. The research results demonstrate that the use of virtual environments reduces testing costs, prevents logistical bottlenecks, and increases workplace safety, providing a controlled and interactive environment for evaluating operational decisions.

KEYWORDS: VR, Digital Twin, Unity 3D, Immersive Simulation, Logistics 4.0

1. Introduction

In the context of globalization and accelerated digitalization, the logistics sector is undergoing continuous transformation. The concept of Logistics 4.0 requires the integration of advanced technologies to increase efficiency, reduce costs, and minimize human errors [1]. Although Augmented Reality (AR) has gained ground in active operations (such as order picking), the technical challenges related to hardware implementation in the real environment make Virtual Reality (VR) remain the ultimate solution for the planning, simulation, and training stages [2].

Unlike AR, which superimposes digital elements onto the physical environment, VR completely immerses the user in a synthetic, computer-generated environment. This decoupling from the physical world eliminates spatial and safety constraints, allowing the testing of logistical scenarios that, in reality, would be extremely costly, dangerous, or time-consuming [3]. The present paper aims to analyse how game development platforms, particularly Unity 3D, can be used as serious tools (Serious Games) for industrial engineering, focusing on simulators and Digital Twins.

2. Current state

2.1. The evolution and adoption of digital twins in logistics

As of 2025-2026, the concept of the "Digital Twin" in logistics has surpassed the static 3D modelling phase, transforming into a dynamic ecosystem based on real-time data synchronization. According to recent market reports, the global digital twin market in logistics is undergoing accelerated expansion, with an estimated compound annual growth rate (CAGR) of over 25% for the 2025-2030 period, driven by the acute need for operational visibility and transparency [3], [4].

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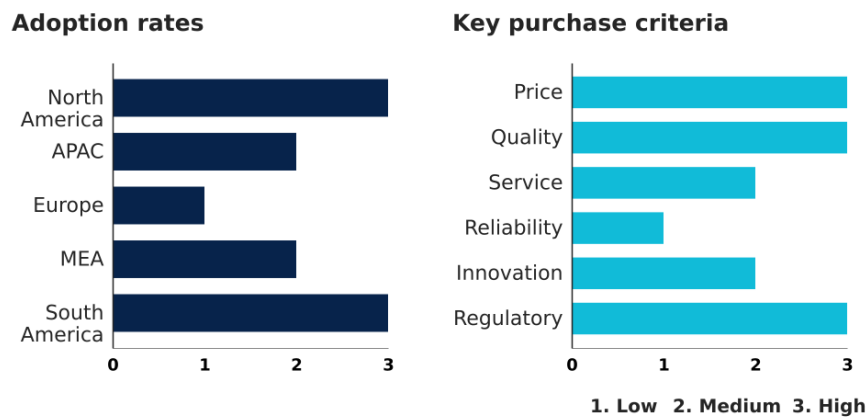


Fig. 1. Customer Landscape of Digital Twin In Logistics Industry [14]

A major identified trend is the integration of Artificial Intelligence (AI) and predictive analytics directly into the structure of Digital Twins. This technological convergence allows systems not only to reflect the physical state of the warehouse but also to actively orchestrate inventory movements, autonomously allocate tasks (Agentic AI), and anticipate equipment failures (Predictive Maintenance) [3], [5]. A concrete example of industrial-level implementation is the DP World project in Dubai (from May 2025), where a high-definition digital twin was integrated into the BoxBay automated storage system, allowing operators to manage and optimize container movements in a fully 3D environment [3].

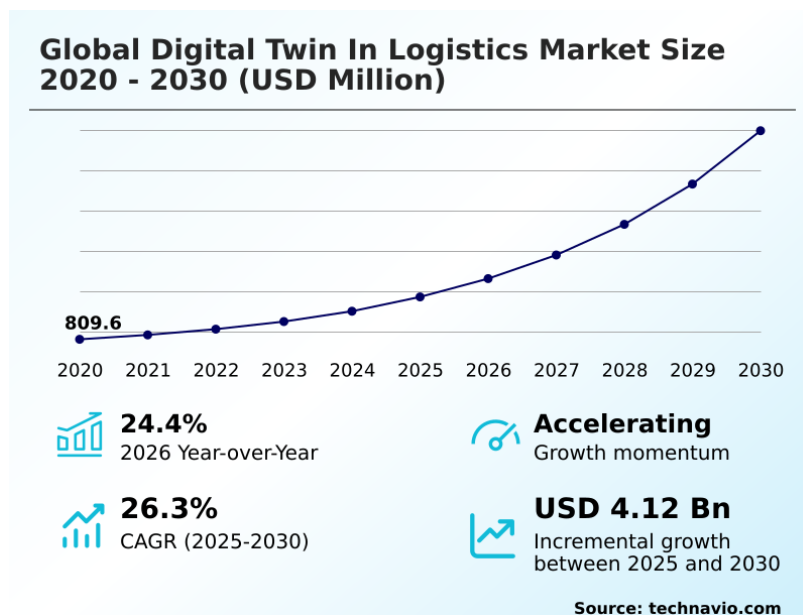


Fig. 2. Global Digital Twin in Logistics Market Size [14]

2.2. The integration of graphic engines (unity) in logistics simulation

To bring these Digital Twins to life, the logistics industry is increasingly relying on Real-Time 3D graphic engines, such as Unity. Through recently emerged dedicated platforms, like Unity Industry and Unity Studio, developers can directly import complex CAD data and

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IoT (Internet of Things) data streams from warehouses to create highly precise physical simulations [6].

Recently published academic research highlights the importance of integrating logistics process simulation with Fully Immersive VR technology. Studies show that the use of VR headsets (HMDs) in logistics modeling exponentially increases the level of engagement and spatial understanding of engineers compared to traditional 2D monitors [7], [8]. Through virtual environments created in Unity, companies report up to a 40% reduction in the time required to configure technological flow simulations, accelerating strategic decisions regarding warehouse layout and resource allocation [3].

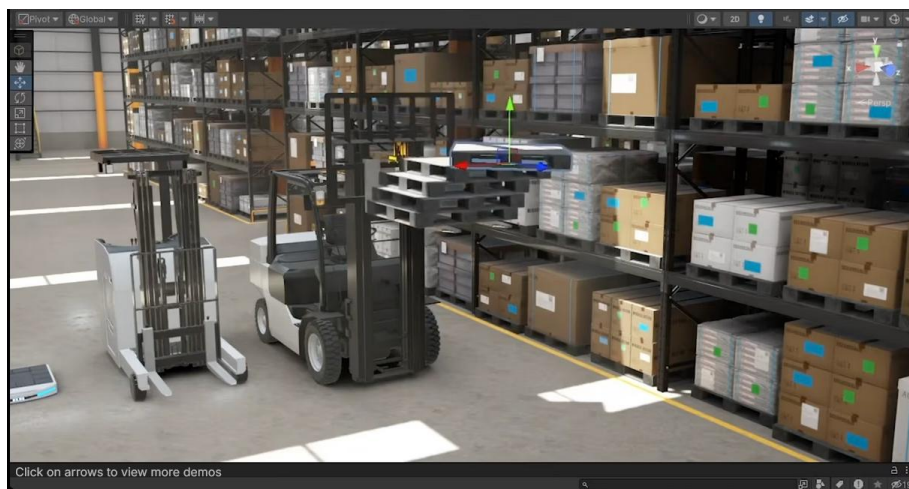


Fig. 3. Unity Industry [15]

2.3. VR simulators for industrial training and safety

The third pillar of the current state of the art is the use of virtual environments for workforce training (VR Training). In the context of a fluctuating labor market, conventional training methods (which require stopping real machinery) are being replaced by immersive platforms that offer safety, cost efficiency, and evaluation based on precise performance data [9].

Research from the 2024-2026 period demonstrates that VR is essential not only for learning standard operating procedures but especially for managing crisis situations. Simulators allow operators to be trained for interventions in case of critical incidents (e.g., major conveyor belt failures, incorrect handling of hazardous materials, fires), providing realistic interaction without endangering personnel's lives [9]. Spatial tracking technology and interactive feedback integrated into Unity-based simulators allow operators to experience situational stress in a safe environment, with their decisions being subsequently corrected and analyzed.

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Fig. 4. Fire extinguishing in Virtual Reality [16]

3. Digital twins in logistics

The concept of a Digital Twin represents an accurate and interactive virtual replica of a physical system, whether it is a piece of machinery, a production line, or an entire warehouse [10]. In industrial logistics, Digital Twins developed in Unity allow engineers and managers to visualize and interact with the warehouse before it is built or modified.

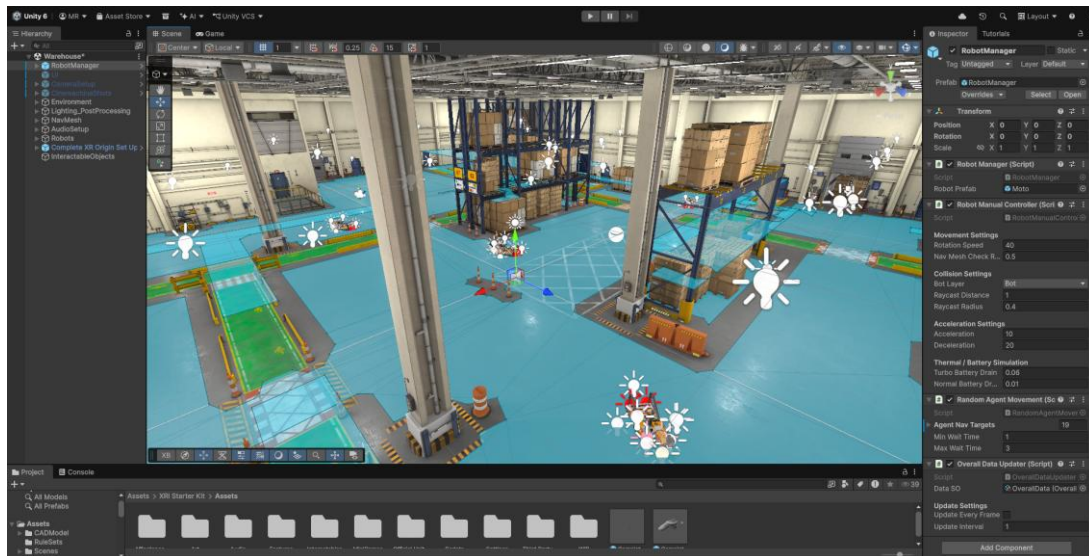


Fig. 5. Simulation of a warehouse

By importing CAD (Computer-Aided Design) models of racks, conveyor belts, and equipment directly into Unity, a 1:1 copy of a warehouse can be built. Using VR headsets, decision-makers can "step" inside this virtual warehouse. This true-to-scale immersion allows for the immediate identification of ergonomic issues: whether an aisle is too narrow for a forklift, if the shelves are too high for operators, or if material flows intersect dangerously [2], [10]. Modifying the layout in Unity takes a few minutes and costs nothing, unlike the physical relocation of racks in reality.

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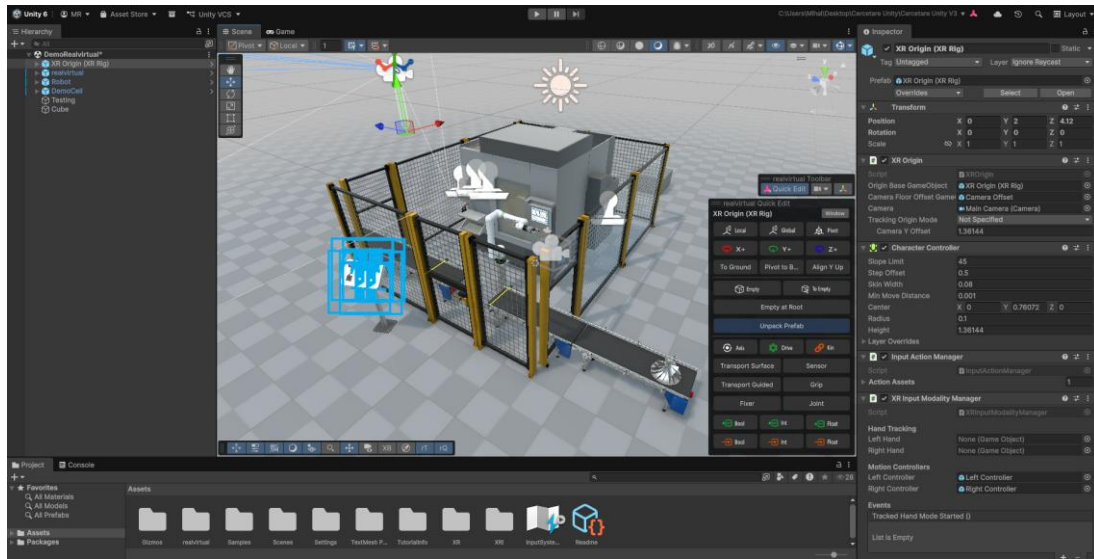


Fig. 6. Simulation of a robot cell using realvirtual.io [17]

Using Unity's physics and scripting (C#) capabilities, mass flow scenarios can be programmed. For example, inbound and outbound goods algorithms can be simulated to visually observe where bottlenecks form on sorting conveyor belts during peak periods. Thus, Unity acts not only as a 3D visualizer but as a process validation tool [10].

4. VR Simulators for training, logistics scenarios and their integration in unity

In addition to planning, the second major utility of VR in logistics is workforce training (VR Training). The high staff turnover in warehouses requires fast, standardized, and safe training methods.

Operating a forklift in a crowded warehouse involves a high risk of accidents and material damage. A simulator created in Unity allows new employees to familiarize themselves with the controls and physics of the machinery in a virtual environment [10]. Using realistic physical interactions, Unity can calculate the weight of the pallets and the machine's center of gravity; if the operator takes a turn too sharply with the forks raised, the virtual forklift will tip over, providing a valuable lesson without any real cost or risk of injury.

Another implementable scenario is training for order preparation (Order Picking). The player (operator) receives an order list on a virtual tablet and must navigate through the 3D warehouse to collect the correct products [1]. The system records reaction times, the chosen route, and the errors made. Repeating these scenarios creates "muscle memory" and spatial orientation, so that, on their first day in the field, the employee already knows the layout of the warehouse [13].

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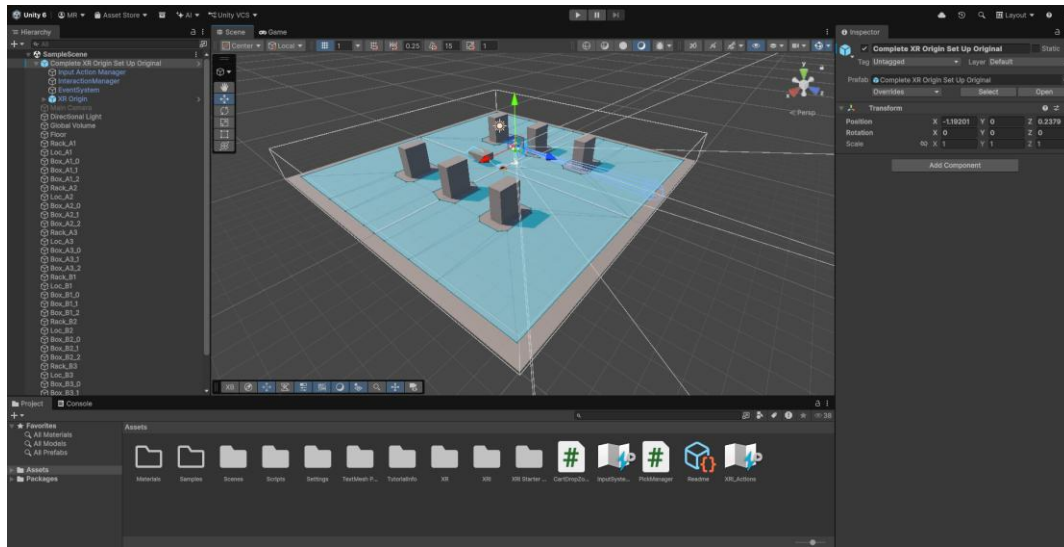


Fig. 7. Application prototype for order picking

VR excels in preparing for rare but critical situations. Scenarios such as a fire breaking out in the battery charging area or a chemical spill from a container can be created in Unity. The operator is trained on how to use a virtual fire extinguisher, how to activate alarms, and what the evacuation routes are—things that are impossible to reproduce realistically and safely in everyday life [10].

To bring these concepts to life, the Unity engine provides specific tools. The XR Interaction Toolkit package facilitates the addition of locomotion mechanics (teleportation or continuous movement) and object manipulation (grabbing boxes, pressing buttons on a control panel). High-fidelity graphics, achieved through the Universal Render Pipeline (URP) lighting systems, ensure the visual immersion necessary to avoid inducing motion sickness. Furthermore, Unity allows Digital Twins to be connected to external databases or servers, transforming the simulation from a static game into a live dashboard connected to the company's WMS (Warehouse Management System) [11], [12].

5. Conclusions

Virtual Reality technology, propelled by accessible and powerful graphic engines such as Unity, represents an essential pillar for the future of Logistics 4.0. The transition from 2D blueprints and paper training manuals to Digital Twins and interactive VR simulators brings undeniable benefits: reducing design costs, increasing efficiency through comprehensive layout testing, and, most importantly, exponentially increasing the safety of human operators. Although technical implementation requires modeling and programming skills, the return on investment (ROI) in industrial VR applications is rapid, confirming the fact that the virtual space is the best testing ground for the real world.

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INTEGRATING INDUSTRY 4.0 CONCEPTS IN THE PRODUCTION OF BEESWAX WRAPS

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***ABSTRACT:** This paper presents the integration of Industry 4.0 concepts into the production of "DarBee" beeswax food wraps, transitioning from an artisanal model to a Smart Factory environment. By implementing Cyber-Physical Systems (CPS), Industrial Internet of Things (IIoT), and advanced robotics, the manufacturing process achieves high-level optimization and scalability. Key results include a 10% reduction in raw material waste through automated dosing, a 15% increase in productivity via digital parameter tuning, and a 20% decrease in unplanned downtime through predictive maintenance. The study demonstrates that digital connectivity and data-driven management effectively replace subjective manual methods, ensuring a sustainable, efficient, and high-performance industrial ecosystem.*

***KEYWORDS:** Industry 4.0, Cyber-Physical Systems, Industrial Internet of Things (IIoT), Cloud Manufacturing, Big Data*

1. Introduction

In the contemporary industrial landscape, the food packaging sector represents one of the major sources of polymer pollution worldwide, exerting severe pressure on terrestrial, aquatic, and atmospheric ecosystems [1]. Dependence on single-use solutions, such as plastic stretch films and aluminum foils, has generated a significant environmental crisis, driven by the extremely slow degradation rate of these materials and the complexity of their recycling process when contaminated with organic residues.

In response to this issue, beeswax food wraps have emerged as a sustainable alternative; however, their production is currently limited to an artisanal manufacturing model. Although effective for local niche markets, manual production methods cannot provide the output volume required for large-scale market penetration.

Therefore, the transition toward Smart Factories, the central pillar of the Fourth Industrial Revolution (Industry 4.0), has become imperative. By integrating advanced technologies such as the Internet of Things (IoT), Cloud Manufacturing, Big Data, and autonomous robots [2], the manufacturing process of beeswax food wraps can be optimized and scaled to industrial levels. Such an approach not only enhances process efficiency but also democratizes consumer access to environmentally friendly products, actively contributing to global awareness regarding environmental protection.

2. Current state of art

2.1. General overview of beeswax food wraps

Beeswax food wraps, marketed under the DarBee brand, represent an innovative and environmentally friendly solution in the field of active packaging. They are designed to replace single-use packaging materials by providing a natural protective barrier that allows food products to "breathe," thereby extending their freshness [1]. The material consists of an organic cotton fabric base impregnated with an optimized blend of beeswax, pine resin, and jojoba oil. The synergy of these ingredients provides natural antibacterial and antifungal properties, transforming the product into a biodegradable and reusable packaging solution.



Fig. 1. Beeswax food wraps [3]

2.2. Fundamentals of Industry 4.0 and the Smart Factory concept

The Fourth Industrial Revolution brings the concept of the Smart Factory to the forefront, defined by the integration of physical and cyber systems [4]. Unlike conventional automation, Smart Factories employ technologies such as the Internet of Things (IoT) for data acquisition and Cloud Computing for processing large volumes of information [5].

In the case of DarBee production, the implementation of these technologies enables the monitoring of critical parameters, such as the melting temperature (optimized at 62°C), thereby ensuring consistent product quality.

2.3. Logistics 4.0 and intelligent resource management

Logistics 4.0 transforms industrial equipment into autonomous entities capable of self-optimization and mutual communication [6]. Using the Digital Twin simulations, processes can be virtually tested before physical execution. For the present project, this translates into predictive inventory management, reducing material waste by approximately 10% and increasing overall productivity by 15% through equipment optimization.

INTEGRATING INDUSTRY 4.0 CONCEPTS IN THE PRODUCTION OF BEESWAX WRAPS

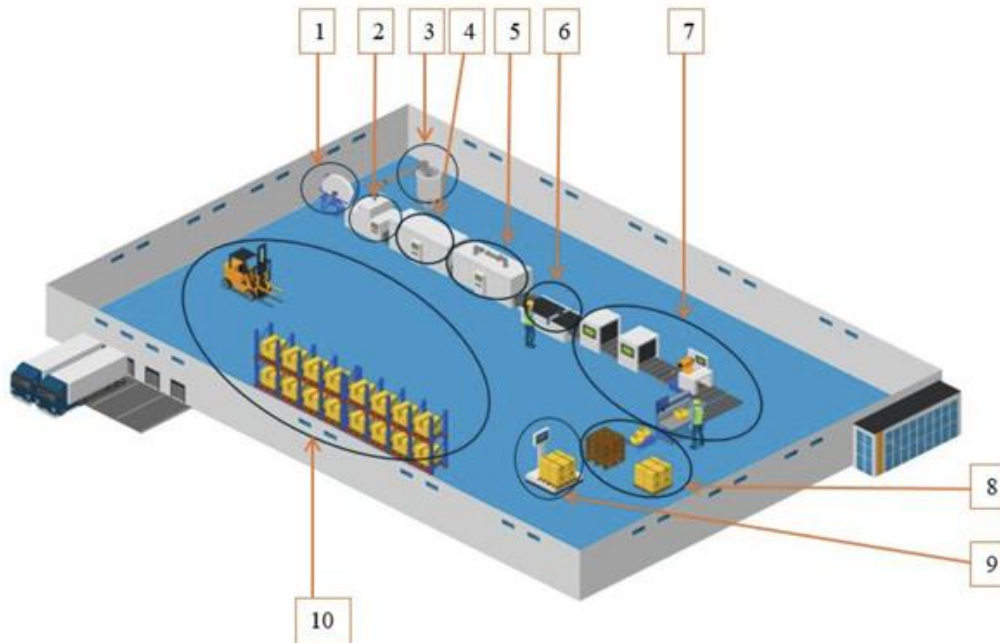


Fig. 2. Workstations within the automated logistics flow

Table 1 Workstations within the flow

Crt. Nr.	Name of the workstation
1	Raw material preparation and fabric unwinding
2	Fabric impregnation
3	Preparation of beeswax, pine resin and jojoba oil mixture
4	Excess material removal
5	Fabric drying
6	Product cutting
7	Packaging
8	Palletizing
9	Stretch wrapping
10	Storage

3. Detailed analysis of workstations from the perspective of intelligent automation

Within the Industry 4.0 paradigm, the production process of DarBee wraps ceases to be a sequence of mechanical operations and becomes a Cyber-Physical System (CPS). This implies a symbiotic integration of physical and digital components. The integrated technological process for DarBee wrap production is structured into ten interdependent workstations, where the concepts of the Internet of Things (IoT) and Cloud Manufacturing ensure efficiency and traceability.

The Cyber-Physical Systems (CPS) concept involves the close integration of physical processes with computational networks and control algorithms. Unlike traditional automation (Industry 3.0), where machines perform predefined tasks without contextual awareness, a CPS monitors physical processes, creates their digital representation, and makes decentralized decisions in real time [7].

INTEGRATING INDUSTRY 4.0 CONCEPTS IN THE PRODUCTION OF BEESWAX WRAPS

The manufacturing process of beeswax food wraps begins with a critical stage for the integrity of the final product, namely the unwinding and positioning of the cotton fabric. Within the Industry 4.0 framework, this workstation is no longer a simple mechanical unwinder but a predictive control node. Using advanced field sensors, the system continuously monitors the fabric tension force. A frequency converter adjusts motor speed in real time to maintain a constant line speed of 0.5 m/s. This digital precision eliminates tension fluctuations that, in manual production, often lead to fiber deformation, thereby ensuring a perfectly flat surface for the impregnation stage. The interoperability between sensors and actuators transforms this workstation into a solid foundation for the entire logistics flow.

The technological core of the Industry 4.0 implementation lies in the impregnation process, where the fabric is saturated with the beeswax, resin, and oil mixture. Here, the Industrial Internet of Things (IIoT) becomes a reality through multiparameter monitoring: the mixture is maintained at the critical temperature of 62°C and an injection pressure of 2 bar. These parameters are managed by a CPS that continuously senses production line speed and autonomously regulates pump flow rates. Rather than relying on fixed dosing, the system employs adaptive dosing: if sensors detect changes in textile density, the PLC instantly recalculates the required pressure to guarantee uniform absorption. This distributed intelligence ensures consistent antibacterial properties while simultaneously reducing raw material waste by 10% through the elimination of overdosing.

Following impregnation, the product undergoes cooling and drying stages, where thermal stability is monitored using Edge Computing technologies. Instead of transmitting data to a remote server, processing occurs locally, enabling the drying tunnel to adjust ventilation and maintain a temperature of 25°C within milliseconds. This rapid response prevents premature wax crystallization, preserving material flexibility. Excess material is removed at a controlled pressure of 1 bar, while the data collected during this phase are stored as Big Data for energy performance analysis. This approach transforms a passive stage (drying) into a digitally optimized process capable of self-regulation according to ambient factory conditions.

The peak of automation is achieved in the cutting and sorting stations, where software-based analysis converges with high-speed execution. A Cognex In-Sight 2000-100 vision sensor inspects each wrap cut by the Festo pneumatic motor, verifying dimensions and alignment at a line speed of 0.5 m/s. Artificial Intelligence plays a crucial role at this stage: the sensor not only measures but also determines product conformity.

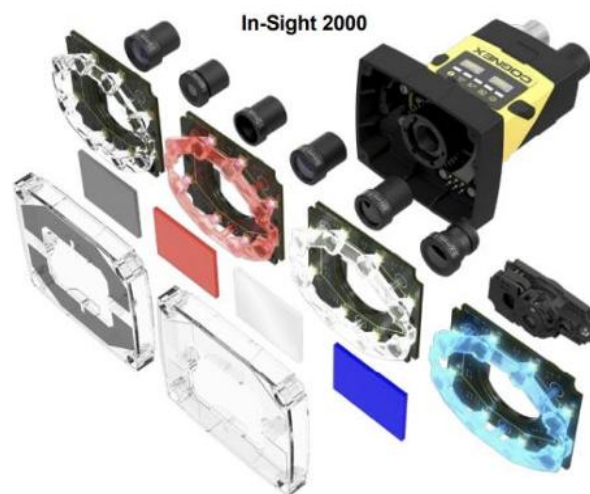


Fig. 3. Vision Cognex In-Sight 2000-100 Sensor [8]

If a component is validated, the PLC commands Delta Robots to initiate the pick-and-place sequence. Delta Robots, symbols of agility in Industry 4.0, employ Conveyor Tracking

INTEGRATING INDUSTRY 4.0 CONCEPTS IN THE PRODUCTION OF BEESWAX WRAPS

algorithms to manipulate products without stopping the conveyor belt. This synergy between AI and parallel robotics eliminates human error and increases productivity by 15%, representing the core element that justifies the technological investment in the DarBee project.



Fig. 4. Delta KR 3 D1200 HM, KUKA Robot [9]

The final stages of packaging, palletizing, and storage integrate the physical product into the digital ecosystem through Logistics 4.0. Each pallet (organized into 24 boxes) becomes a data node within an extensive network. By creating a Digital Twin of each production batch, the system stores its complete manufacturing history. This full traceability enables not only efficient inventory management but also predictive maintenance of the entire production system. By monitoring component wear during operation, the system can anticipate maintenance requirements, reducing downtime by 20% and ensuring the long-term sustainability of the business.

4. Logistics flow management and economic analysis within the Industry 4.0 ecosystem

The objective of the project is to digitalize the DarBee production line in order to increase process efficiency and sustainability through Industry 4.0 solutions. To evaluate the success of this implementation, the following Key Performance Indicators (KPIs) have been established:

- Reduction of raw material consumption by 10% within 6 months through the implementation of an automated monitoring system for the dosing of the heated mixture of beeswax, pine resin, and jojoba oil.
- Increase in production line productivity by 15% within 8 months through optimization of equipment operating parameters.
- Reduction of unplanned downtime by 20% within 12 months through the implementation of an IoT sensor-based predictive maintenance system.

The implementation of Smart Manufacturing concepts within the DarBee production line required a complete restructuring of logistics flows, from the procurement of organic raw materials to the storage of finished products. Flow management was achieved through rigorous activity planning, ensuring interoperability among analysis, digital design, and execution stages. Each logistics task was scheduled to minimize downtime, enabling a seamless transition between the impregnation area and the SCADA-controlled cutting station.

Resource management within the DarBee production line is based on the interoperability concept, transforming the production flow into a Cyber-Physical System. According to the Resource Overview report, optimization no longer focuses solely on manual labor but rather on the digital synchronization of equipment to enable decentralized decision-making. Consequently, the system monitors raw

INTEGRATING INDUSTRY 4.0 CONCEPTS IN THE PRODUCTION OF BEESWAX WRAPS

material consumption in real time and adjusts production flow to maintain a speed of 0.5 m/s without continuous human intervention.

This proactive organization enables the transition from traditional maintenance to predictive maintenance, utilizing process data to anticipate equipment wear and reduce downtime by 20%. The integration of resources into a unified digital network is the key factor justifying the investment of RON 289,777.80, ensuring maximum utilization of production capacity and a 10% reduction in losses.

RESOURCE OVERVIEW

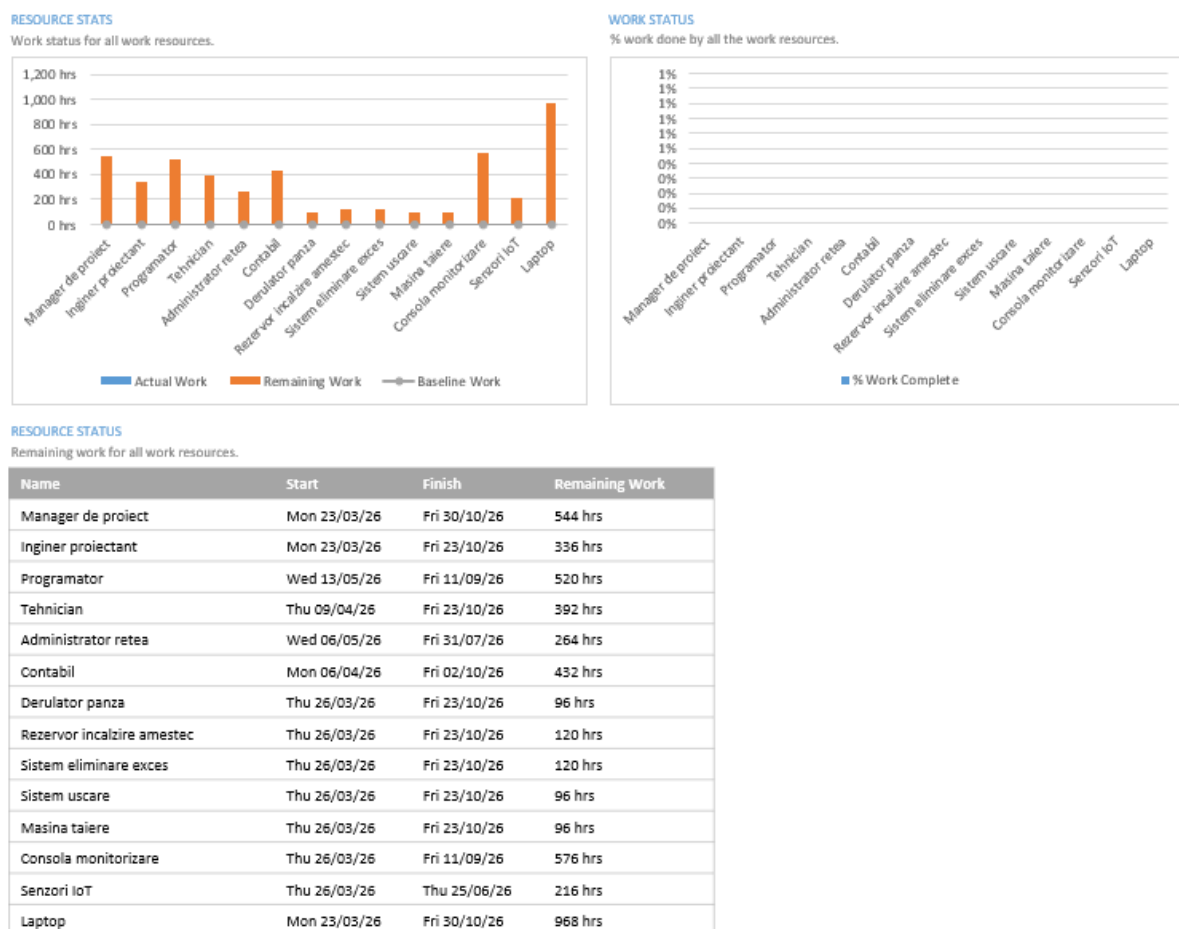


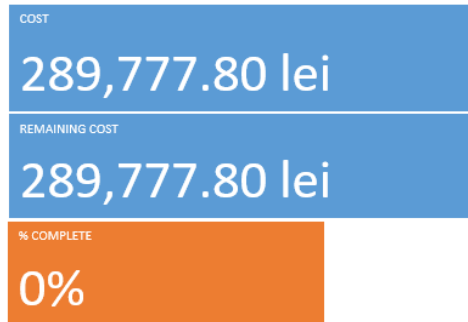
Fig. 5. Resource Overview

The total budget of RON 289,777.80 reflects the complexity of integrating advanced technologies. Financial flow management was segmented to identify the contribution of fixed costs (Festo equipment, Cognex sensors) and variable costs (raw materials and energy). This detailed analysis demonstrates that the Industry 4.0 investment is justified through long-term operational cost reductions, achieved by decreasing material waste by 10% and optimizing wax and resin consumption through intelligent dosing.

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COST OVERVIEW

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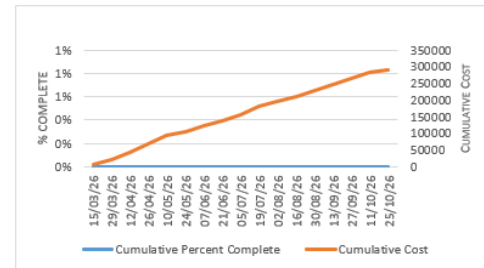
COST STATUS

Cost status for top level tasks.

Name	Actual Cost	Remaining Cost	Baseline Cost	Cost	Cost Variance
Etapa 1. Analiza procesului de fabricare actual	0.00 lei	25,290.80 lei	0.00 lei	25,290.80 lei	25,290.80 lei
Etapa 2. Identificarea problemelor	0.00 lei	33,265.00 lei	0.00 lei	33,265.00 lei	33,265.00 lei
Etapa 3. Proiectarea solutiei	0.00 lei	57,690.00 lei	0.00 lei	57,690.00 lei	57,690.00 lei
Etapa 4. Implementarea	0.00 lei	63,182.00 lei	0.00 lei	63,182.00 lei	63,182.00 lei
Etapa 5. Evaluare si optimizare	0.00 lei	110,350.00 lei	0.00 lei	110,350.00 lei	110,350.00 lei

PROGRESS VERSUS COST

Progress made versus the cost spent over time. If % Complete line below the cumulative cost line, your project may be over budget.



COST STATUS

Cost status for all top-level tasks. Is your baseline zero?

[Try setting as baseline](#)

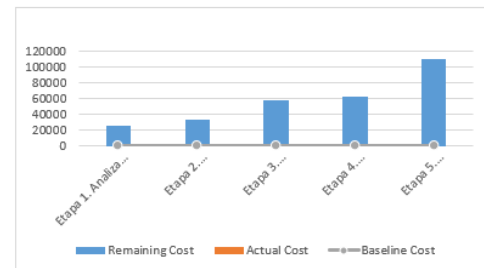


Fig. 6. Cost Overview

The efficiency of logistics management in the digital era is measured through performance indicators (KPIs) correlated with financial stability. The projected Cash Flow demonstrates the sustainability of the project throughout the eight-month implementation period. By achieving the objective of increasing productivity by 15% and implementing predictive maintenance (20% downtime reduction), the system ensures accelerated return on investment, transforming the DarBee factory into a successful model for the circular and digital economy.

INTEGRATING INDUSTRY 4.0 CONCEPTS IN THE PRODUCTION OF BEESWAX WRAPS

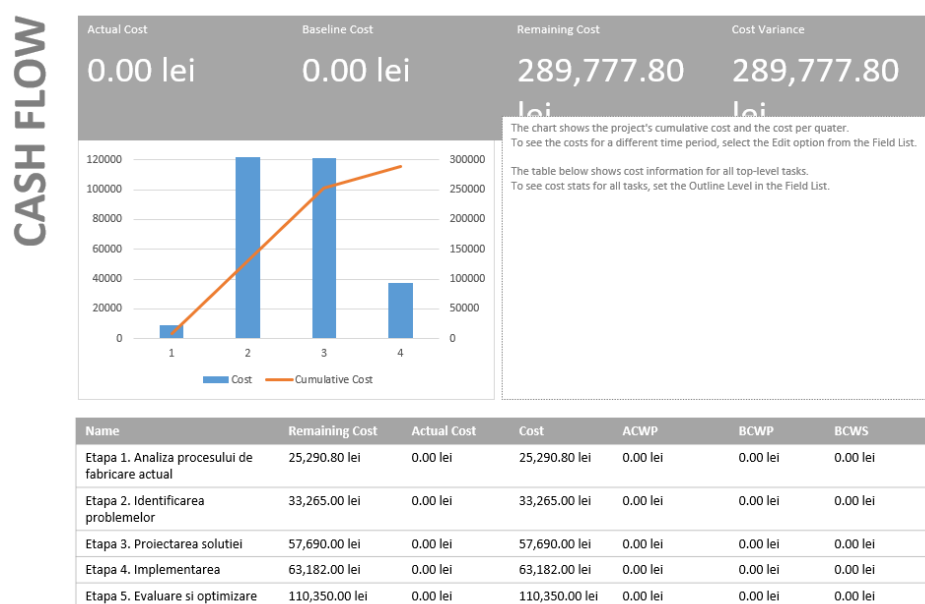


Fig. 7. Cash Flow

5. Conclusions

The implementation of Industry 4.0 concepts in the manufacturing process of beeswax food wraps marks a fundamental transition from artisanal production, based on intuition and manual labor, to an intelligent and predictive industrial ecosystem. Whereas product quality in the manual approach depended exclusively on operator experience and subjective visual inspection, digitalization now enables continuous monitoring of every stage, eliminating variability and human errors that frequently resulted in raw material waste.

The transition from manual manufacturing to the Industry 4.0 model represents the shift from a craft-based process characterized by human errors and inefficiencies to a data-driven Smart Factory. While product quality was variable under traditional conditions, the integration of digital technologies now enables complete control of the production flow, transforming the manufacturing line into a system capable of real-time self-optimization.

In essence, the adoption of Industry 4.0 concepts demonstrates that efficiency no longer derives from physical effort but from connectivity. The transition to a digital ecosystem ensures a level of precision and sustainability unattainable through conventional methods. Consequently, the project confirms that the future of engineering lies in complete digitalization, the only approach capable of guaranteeing maximum performance with minimal resource consumption.

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COMPARATIVE ANALYSIS OF MULTILAYER POLYMERS IN PACKAGING EXTRUSION AND THERMOFORMING PROCESSES

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ABSTRACT: This paper presents a techno-scientific analysis of multilayer polymer structures widely used in the high-barrier food packaging industry. The primary objective of the research is the comparative evaluation of the rheological, thermomechanical, and barrier behavior of polymer combinations successively subjected to industrial coextrusion and thermoforming (vacuum or plug-assisted) processes.

The results reveal the critical importance of layer compatibilization through the use of tie layers and highlight the optimal processing windows required to prevent structural defects, such as delamination or excessive localized thinning in the corner zones of deep-drawn thermoformed packaging.

KEYWORD: Multilayer, Coextrusion, Thermoforming, EVOH.

1. Introduction

The modern polymer packaging industry faces a dual challenge: on the one hand, the need to extend the shelf life of perishable products by providing superior barrier properties to oxygen, water vapor, and aromatic compounds; on the other hand, the imperative to reduce the carbon footprint and optimize material consumption by reducing structural weight. Classic monolayer polymers (such as plain polyethylene or polypropylene) cannot simultaneously meet all these strict requirements. For this reason, the predominant technological solution is the use of flexible or rigid multilayer structures.

Multilayer structures allow the synergistic combination of properties specific to each polymeric component. For example, polyolefins offer an excellent moisture barrier and very good thermal weldability, while specialized polymers such as ethylene-vinyl alcohol or polyamide provide an exceptional gas barrier and increased mechanical strength. The integration of these materials into a single film is achieved through the coextrusion process, often followed by a thermoforming step to obtain trays, blisters, or three-dimensional containers.

2. Current state

A complex multilayer structure is designed geometrically and functionally according to the final application of the packaging.

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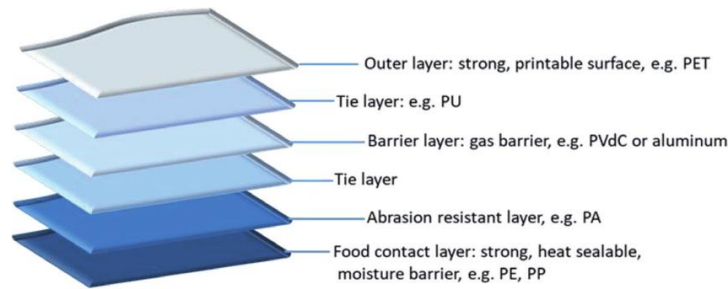


Fig. 1. Schematic diagram of the cross-section through a 5-layer film [8]

A top industrial example is the asymmetric structure of the type: Polyethylene terephthalate (PET) / Polyurethane (PU) / Polyvinylidene chloride (PVdC) / Polyurethane (PU) / Polyamide (PA) / Polypropylene (PP). The component layers of this configuration can be generically classified according to their technological role [3].

Table 1 Classification and Architecture of Multilayer Polymeric Materials

Layer Type	Polimer Utilizat	Funcție Principală în Structură
Exterior Structural	Polyethylene terephthalate (PET)	Mechanical impact resistance, high thermal resistance upon contact with sealing jaws, gloss, and print support.
Adhesive	Polyurethane (PU)	Tie layer is applied by lamination to ensure strong interfacial adhesion between the structural layers and the barrier layer.
Gas and Moisture Barrier	Polyvinylidene chloride (PVdC)	Blocking the penetration of oxygen and carbon dioxide; unlike other polymers, it retains its barrier properties even at 100% humidity.
Intermediate Structural	Polyamide (PA)	Ensuring puncture resistance, high elasticity, and uniform distribution during the deep thermoforming process.
Sealing / Bonding	Polypropylene (PP)	Inner layer that comes into direct contact with the product; ensures hermetic thermal welding and withstands sterilization temperatures of over 121°C.

3. Rheological and thermomechanical properties of polymer melts

The behavior of polymers during coextrusion is dictated by their rheological properties in the molten state. Polymer melts are non-Newtonian fluids, exhibiting pseudoplastic behavior, where dynamic viscosity decreases with increasing shear rate. For modeling the flow in the channels of the extrusion die, the power-law equation is used:

Power-law equation

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$$\tau = K \cdot (\dot{\gamma})^n \quad (1)$$

Where:

τ = Shear stress [Pa]

K = Fluid consistency index [Pa x sⁿ]

$\dot{\gamma}$ = Shear rate [s⁻¹]

n = Flow behavior index / Rheological behavior index ($n < 1$ for polymers)

When different polymers flow together in a laminar regime, if the viscosity ratio between two adjacent layers exceeds a critical value ($n_1/n_2 > 3.0$ or $n_1/n_2 < 0.3$), the phenomenon of encapsulation of the more viscous layer by the more fluid one or wave-type interfacial instability occurs, a defect that destroys the optical uniformity of the film [1].

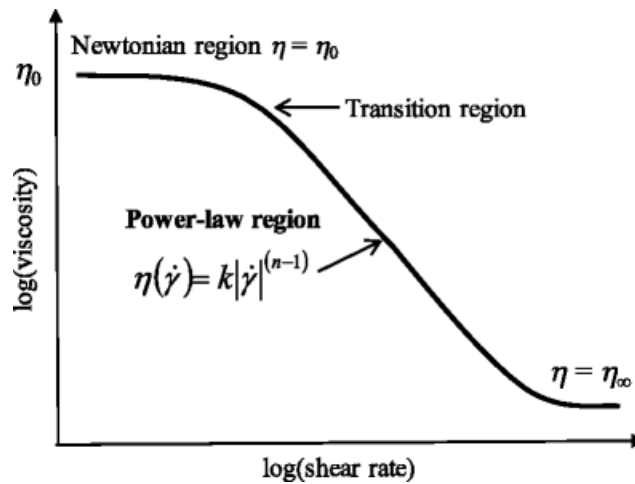


Fig. 2. Rheological graph of polymers [6]

Viscosity also depends on temperature according to the Arrhenius-type equation for semi-crystalline polymers at temperatures well above T_m :

Arrhenius-type equation for semi-crystalline polymers

$$\eta = \eta_0 \cdot \exp\left(\frac{E_a}{R \cdot T}\right) \quad (2)$$

Adjusting the temperatures in the zones of each individual extruder represents the main

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industrial method for equalizing viscosities at the meeting point of the flows in the coextrusion feedblock [1].

4. The multilayer polymer coextrusion process

Coextrusion represents the primary technology by which two or more polymer melts originating from independent extruders are combined into a single fluid geometry before solidification. There are two established methods in the industry: cast film coextrusion and blown film coextrusion [1], [3].

4.1. Cast film coextrusion

In flat film production, the combined polymer melts stream exits a wide, rectangular slot die (commonly referred to as a coat-hanger die) designed to distribute the multi-layered fluid uniformly across the entire web width.

Upon exiting the die lips, the molten curtain is immediately drawn down and "quenched" against a highly polished, internal water-cooled steel cylinder known as the chill roll, typically maintained at a controlled temperature range of 20°C to 40°C. To ensure uniform heat transfer and prevent defects like gauge variations or surface blemishes, the molten web must be tightly pinned to the chill roll. This is industrially achieved using one of two primary methods:

Air Knife: A high-velocity jet of controlled air presses the melt against the roll immediately at the point of contact.

Vacuum Box: Draws out the air trapped between the molten film and the roll surface from the underside, preventing air bubbles and ensuring excellent surface replication. [1].

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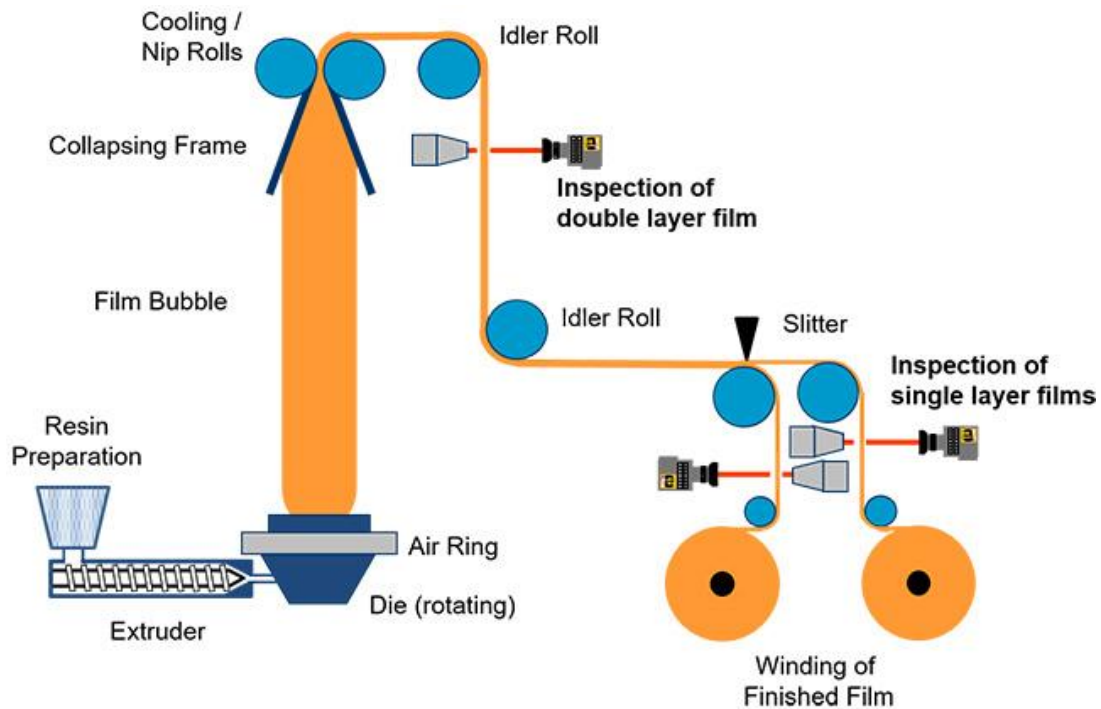


Fig. 3. Cast Film Coextrusion [5]

4.2. Blown film coextrusion

In the blown film process, the melts are directed into a concentric circular die. The film emerges as a tube that is inflated with compressed air to form a bubble and, simultaneously, is pulled upwards by a pair of nip rollers, achieving a balanced biaxial molecular orientation in both the machine and transverse directions. This provides excellent puncture resistance, an essential property for flexible packaging intended for hard or frozen foods. [3].

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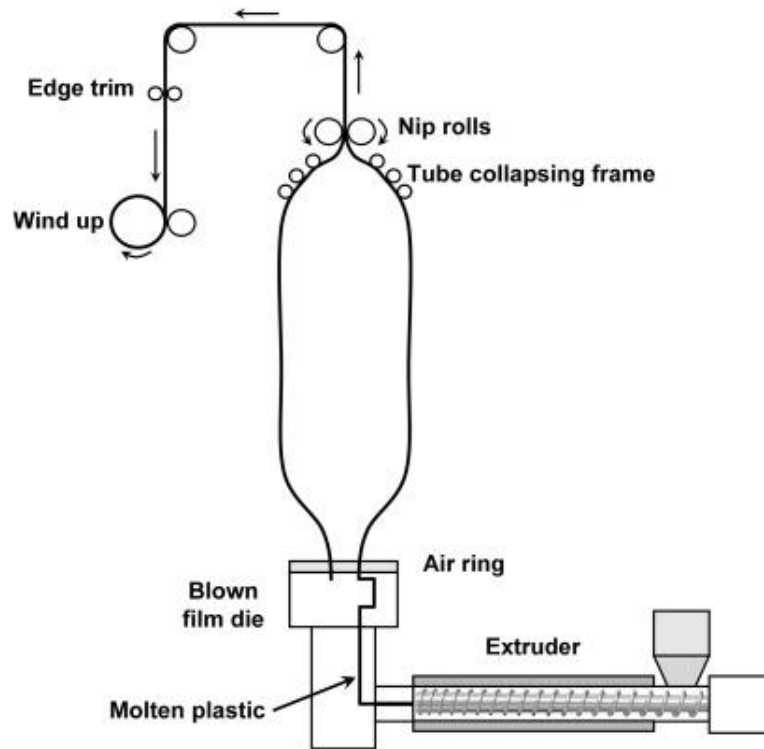


Fig. 4. Blown Film Coextrusion [4]

5. The thermoforming process of multilayer films

Thermoforming is a secondary process in which the flat coextruded film is reheated to an optimal processing temperature, located in the thermomechanical plastic deformation window of the material, and then molded onto a die by applying pressure or vacuum [2].

5.1. The Thermoforming Window

For multilayer structures, determining the optimal temperature is complex because each layer has different glass transition (T_g) and melting points (T_m). The optimal window is defined by the equation:

Thermoforming window equation

$$\max(T_{g,i}) < T_{\text{proces}} < \min(T_{m,j}) \quad (3)$$

For a polypropylene/ethylene-vinyl alcohol/polypropylene structure, the film temperature must be strictly maintained between 145°C and 155°C, otherwise resulting in either excessive rigidity and internal stresses or an uncontrolled gravitational sagging of the hot film [2], [3].

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5.2. Biaxial Stretching Mechanics and Plug Assistance

During deep-draw thermoforming (draw ratio $H/D > 0.5$), simple compressed air cannot ensure uniform thickness because the material first touches the upper edges of the mold where it cools instantly, leaving the lower corners very thin. To solve this problem, a mechanical assist plug made of materials with low thermal conductivity is used. The plug mechanically pushes the center of the hot film into the mold, pre-distributing the material before applying the final jet of compressed air at 6-7 bar [2].

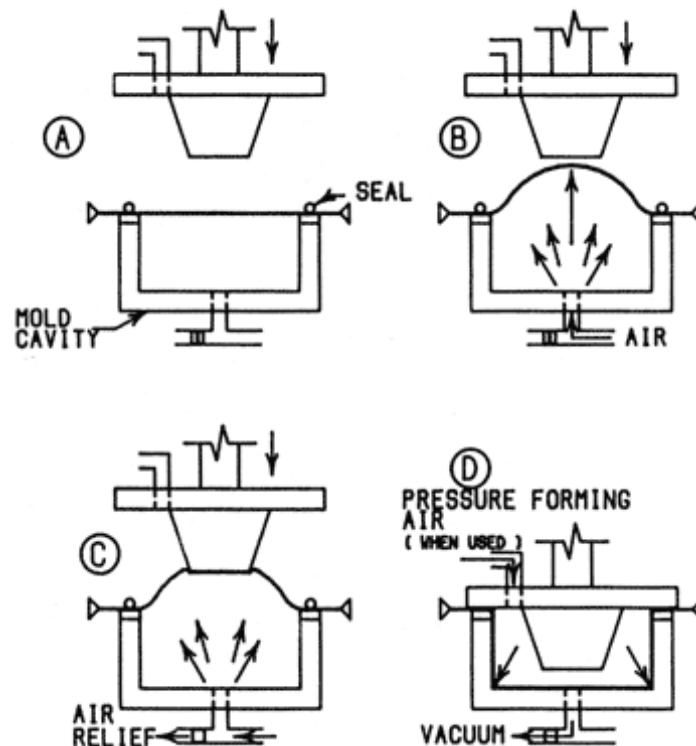


Fig. 5. Four-step schematic of the plug-assisted thermoforming process [7]

6. Comparative Performance Evaluation of Polymer Structures

Within the research, three major multilayer polymer architectures used in the packaging industry were comparatively evaluated, each having distinct permeability and structural resistance characteristics [3].

- **Polypropylene / Tie layer / Ethylene-vinyl alcohol / Tie layer / Polypropylene:** Designed for ready-meal trays, subjected to thermal sterilization at 121°C. It offers an excellent water vapor barrier and an outstanding oxygen barrier, but processing is difficult and requires mandatory mechanical assistance [3].
- **Polyethylene / Tie layer / Polyamide / Ethylene-vinyl alcohol / Polyamide / Tie layer / Polyethylene:** Used for deep vacuum or modified atmosphere packaging of

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cheeses and fresh meat. The polyamide layers structurally protect the barrier layer against micro-cracking, offering high elasticity and maximum gas isolation [3].

- **Amorphous polyethylene terephthalate / Tie layer / Polyethylene:** Used for pharmaceutical blisters and rigid transparent trays. It presents a medium to good barrier but behaves excellently in thermoforming due to the wide highly elastic state range of the amorphous polyester [2], [3].

Table 2. Comparative Technical Permeability Data

Packaging Structure	Total Thickness (μm)	Oxygen Permeability (cc/m ² ·zi·bar) at 23°C,0%RH	Water Vapor Permeability (g/m ² ·zi) at 38°C,90%RH	Impact Resistance (N)
Polypropylene / EVOH / Polypropylene	400	< 0.4	0.2	22
Polyethylene / Polyamide / EVOH / Polyethylene	150	< 0.1	0.9	45
Polyethylene terephthalate / Polyethylene	350	12.0	2.1	31

7. Defect Analysis in Multilayer Processing and Predictive Methods

The integrated processing of coextrusion and thermoforming can generate unique defects caused by the heterogeneous nature of the combined material [4], [3].

7.1. Interfacial Delamination

Tie layers typically maleic anhydride-grafted polyolefins act as essential molecular bridges to stabilize the immiscible polymer boundaries within a multilayer film. The functionalized anhydride groups form strong covalent and hydrogen bonds with polar barrier resins like EVOH or polyamide, while the polyolefin backbone co-crystallizes and entangles with non-polar structural layers such as polyethylene or polypropylene. This combined chemical and physical interlocking is what prevents the distinct material phases from separating under normal processing conditions.

The development of this interfacial bond strength is strictly dependent on maintaining optimal thermal conditions during the coextrusion process. If the melt temperature drops below the critical chemical activation threshold of the grafting agent, the interfacial reaction fails to go to completion, resulting in poor molecular interlocking across the layers. This leaves the film with a sub-standard interfacial strength, causing the peel adhesion force to drop

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significantly below the critical industrial safety limit of 200 N/m. [1], [3].

7.2. Barrier Layer Rupture (Pinholing Formation)

Because ethylene-vinyl alcohol is a high-crystallinity polymer, its hot elongation at break is lower than that of polyethylene. During rapid thermoforming, if the deformation rate exceeds a critical speed, the barrier layer ruptures microscopically on the inside, forming pinholes. The defect is invisible to the naked eye but destroys the oxygen barrier. The probability of microscopic structural defects occurring depending on applied stress can be modeled by the Weibull reliability function:

$$\begin{aligned} &\text{Weibull reliability function} \\ R(\sigma) &= \exp \left[- \left(\frac{\sigma}{\sigma_0} \right)^\beta \right] \end{aligned} \quad (4)$$

Where σ is the applied biaxial tensile stress, σ_0 represents the characteristic rupture stress of the barrier layer, and β is the shape parameter of the structural defect [4].

8. Sustainability and Recyclability Considerations

While multilayer films efficiently extend food shelf life, their material heterogeneity severely complicates post-consumer recycling. Automated Near-Infrared (NIR) sorting facilities identify only the majority surface polymers, causing complex films to be misrouted into monolayer recycling streams. During mechanical re-extrusion, the incompatible embedded barrier polymers separate, leading to thermal degradation and contamination of the recycled resin. To mitigate stream contamination, current European circularity guidelines dictate a strict transition toward mono-material packaging:

The 95% Rule: Packaging is classified as recyclable only if at least 95% of its total mass consists of a single structural polyolefin (PE or PP).

Barrier Cap: Functional barrier layers (like EVOH) are strictly limited to a maximum of 5% of the total packaging mass.

Molecular Compatibilization: To safely process this 5% barrier fraction without ruining the secondary recycling, tie layers must contain sufficient reactive grafting agents. During recycling, these agents act as compatibilizers, emulsifying the barrier remnants evenly into the new polyolefin matrix. [3],[10].

9. Case Study: Wall Thickness Optimization of a Barrier Tray

A comparative experimental study was carried out on an industrial line for manufacturing a rectangular tray with dimensions of 200 x 150 x 50 mm, using two distinct structures with the same initial film thickness of 400 μm [2], [3].

Scenario 1 (Polypropylene/EVOH/Polypropylene without mechanical assistance -

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vacuum only): The nominal thickness of the tray bottom dramatically decreased to 35 μm , and in the lower corners, the barrier layer fell below 1.2 μm . Tests indicated high localized permeability, reducing the product's shelf life from 21 days to just 6 days [3].

Scenario 2 (Polyethylene/Polyamide/EVOH/Polyethylene using plug-assisted mechanics): Due to the presence of elastic polyamide layers and the use of a plug heated to 80°C, the thickness distribution was uniform. The minimum thickness at the corners was 120 μm , and the barrier layer was maintained above the critical safety limit of 4.8 μm , preserving optimal isolation properties [2], [3].

The technological efficiency of the process was calculated using the formula:

Thermoforming technological efficiency index

$$E_{\text{tech}} = \left(\frac{G_{\text{minim}}}{G_{\text{nominal}}} \right) \cdot 100 [\%] \quad (5)$$

In Scenario 1, $E_{\text{tech}} = 8.75\%$, while in Scenario 2 (optimized), $E_{\text{tech}} = 30.0\%$, demonstrating a massive structural improvement in the production process through the correct use of mechanical parameters [2].

10. Conclusions

The detailed comparative analysis within this project highlights that designing multilayer polymer structures represents a complex balance between technical barrier requirements, industrial processing capacity, and stringent economic and ecological sustainability norms.

Each analyzed system finds its optimal applicability zone: polypropylene-based structures are ideal for rigid packaging subjected to severe heat treatments (sterilization), while flexible systems based on polyamide and polyethylene offer the elasticity and crack resistance necessary for forming deep bags. The success of the integrated extrusion and thermoforming process depends directly on the rigorous control of flow parameters at the interfaces and the careful design of thermomechanical windows, paving the way to produce high-performance packaging.

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12. Notations

The following symbols are used in this paper:

A_{SL} = lateral surface area [mm^2];

A_t = total area [mm^2]

Research on Hybrid Carbon Footprint Evaluation for Virtual Industrial Enterprises

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ABSTRACT: The transition to Industry 5.0 and stricter environmental regulations requires transparent and verifiable Product Carbon Footprints (PCF). Current industrial software mainly uses static Life Cycle Assessments (LCA) and historical averages, which can differ from real manufacturing emissions. This paper proposes a hybrid dynamic PCF model for Virtual Industrial Enterprises, combining ERP/PLM data, IoT sensor telemetry, and real-time energy grid carbon intensity to generate an accurate Digital Product Passport (DPP). A case study on a CNC-milled automotive suspension control arm shows that dynamic scheduling and real-time monitoring can reduce Scope 2 manufacturing emissions by up to 46% compared to traditional static methods.

KEYWORDS: *Product Carbon Footprint, Dynamic LCA, Virtual Enterprise, IoT*

1. Introduction

The virtual industrial enterprise (ve) represents a dynamic organizational paradigm based on the temporary cooperation of independent entities (nodes) to respond rapidly to market opportunities. In the context of industry 5.0, this model faces a critical new constraint: verifiable sustainability. Delivering a product rapidly and cost-effectively is no longer sufficient; it must be accompanied by a transparent ecological passport [1]. The product carbon footprint (pcf) has emerged as the dominant non-financial key performance indicator (kpi) across global supply chains.

However, recent literature and industrial practice highlight a major discrepancy between the carbon footprint estimated during the initial design phase and the actual emissions generated during the physical execution phase [2]. By transitioning from retrospective, static estimations to dynamic, sensor-driven measurements, this research aims to provide an operational framework for accurate PCF assessment within distributed manufacturing networks.

1.1. Research Objectives and Hypothesis

The primary objective of this paper is to develop a hybrid mathematical and architectural model capable of transitioning PCF assessment from a static approximation to a dynamic measurement, specifically tailored for the interoperability requirements of a Virtual Enterprise. The specific objectives include:

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Fusing static design data (BOM from PLM/ERP) with dynamic, high-frequency shop-floor telemetry (IoT/MES).

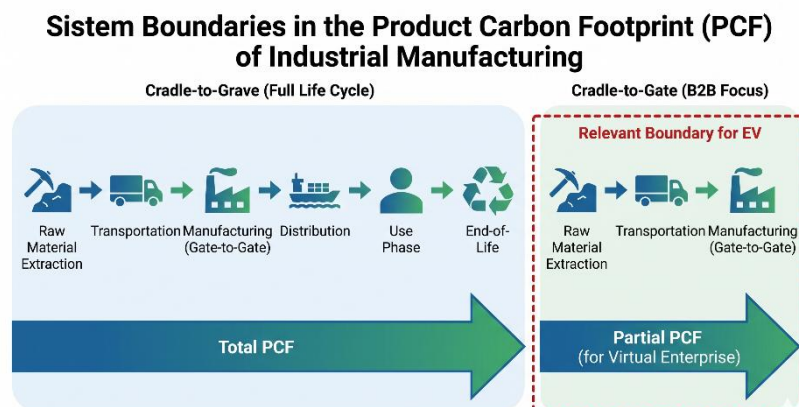
Integrating real-time fluctuations of national energy grid carbon intensity into the footprint calculation.

Structuring the output into a verifiable Digital Product Passport (DPP).

Hypothesis: It is hypothesized that by replacing annual grid averages and theoretical machine consumption with dynamic, time-integrated measurements (Dynamic LCA), the calculated Scope 2 manufacturing emissions will show significant variance compared to traditional static accounting. Furthermore, leveraging this dynamic data through a Digital Twin will enable smart scheduling, potentially reducing the operational carbon footprint.

State of the Art

To ensure scientific validity, carbon management systems must align with international standards, notably ISO 14067 [3]. Within a Virtual Enterprise, the most relevant system boundary is the "Cradle-to-Gate" approach. This encompasses the extraction of raw materials, transportation, and the manufacturing process up to the factory gate, preparing the component for B2B delivery [4].



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Fig. 33 Visual representation of System Boundaries: Cradle-to-Gate vs. Cradle-to-Grave

Currently, the industrial software market integrates sustainability modules into PLM platforms [5]. Notable examples include:

Siemens NX (Sustainability Impact Analysis): Utilizes AI algorithms and databases to provide early feedback during the CAD phase. While excellent for mass reduction, its calculations remain theoretical and ignore specific machine efficiency [6].

PTC Windchill: Focuses on the "Green BOM" and supply chain aggregation. It standardizes data across an extended enterprise but acts as a management tool rather than a physical measurement system [7].

The primary gap identified in current literature is the reliance on static data [8]. Traditional software assumes a milling process consumes a fixed X kWh/kg. Consumption depends on tool wear, material hardness, and the dynamic "energy mix" manufacturing at night using wind energy has a fundamentally different footprint than daytime production using coal.

2. Proposed Hybrid Architecture and Methodology

To address the limitations of static LCA, this paper details a hybrid mathematical model and technical architecture [9]. The goal is to create an uninterrupted "Digital Thread" between theoretical design data and physical shop-floor execution.

3.1.Data Fusion Architecture

The proposed system fuses data from three distinct informational tiers [10]:

Static Planning Level (ERP/PLM): Extracts the Bill of Materials and standard emission factors associated with raw material extraction (Scope 3 upstream) [11].

Dynamic Internal Level (IoT/MES): Utilizes high-frequency current sensors on CNC panels. Data is transmitted via MQTT and OPC UA protocols to measure exact energy consumption [12].

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Dynamic External Level (Energy Grid API): Interrogates national energy grid APIs (e.g., ENTSO-E) to retrieve real-time carbon intensity I_{CO_2} in gCO_2e/kWh [13].

To bridge the semantic gap between these heterogeneous data sources, the architecture utilizes Asset Administration Shells (AAS) as standardized digital representations of the physical assets. This ensures that energy data from a CNC machine in one node of the Virtual Enterprise is immediately interpretable by the central ERP system of the integrator, regardless of the hardware manufacturer. Furthermore, the integration of IDS Connectors ensures that raw operational data remains under the supplier's control, sharing only the calculated carbon result, thus protecting industrial intellectual property within the collaborative network.

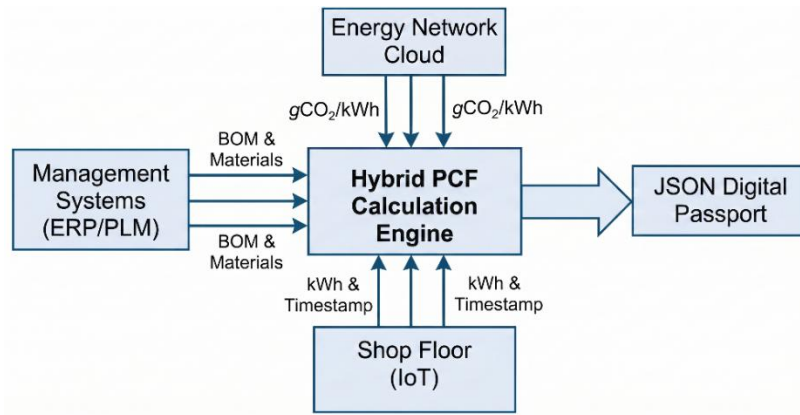


Fig. 34 Data Fusion Architecture Diagram

3.2. Mathematical Formulation

The total carbon footprint of a manufactured part (PCF_{total}) is calculated as:

$$PCF_{total} = E_{mat} + E_{mfg} + E_{aux} \quad (1)$$

The Static Component (Materials): Unlike simplified models, our approach mandates the use of gross mass (M_{brut_j}) to account for the ecological impact of machining waste:

$$E_{mat} = \sum_{j=1}^m (M_{brut_j} \cdot EF_{extraction_j}) \quad (2)$$

The Dynamic Component (Manufacturing): The core innovation is transitioning to a temporal integration method [13]. The footprint of each operation is the integral of absorbed power multiplied by the carbon intensity at time t . Using a Riemann sum approximation for discrete IoT intervals (Δt):

$$E_{mfg} \approx \sum_{i=1}^n \sum_{k=1}^K (P_i(t_k) \cdot I_{CO2}(t_k) \cdot \Delta t) \quad (3)$$

3. Comparative Case Study: Static vs. Dynamic PCF Evaluation

The case study demonstrates the applicability of the proposed model using literature-based and representative industrial data. The objective is to explicitly compare the carbon footprint results obtained via the traditional Static LCA method versus the proposed Dynamic IoT-based method.

4.1. Component Specification and Data Provenance

The selected part is an Automotive Lower Suspension Control Arm, CNC-machined from a solid billet of Aluminum 7075-T6. Input data is grounded in established industrial databases:

- **Material Profile:** The emission factor ($11.2 \text{ kgCO}_{2e}/\text{kg}$) is sourced from the Ecoinvent 3 database [11]. Gross mass (M_{brut}) is 2.5 kg; net mass (M_{net}) is 1.5 kg.
- **Machine Power:** Average power draw values for Band Saw cutting, 3-Axis CNC Milling, and CNC Drilling are derived from technical specifications of standard industrial equipment.
- **Grid Carbon Intensity (I_{CO2}):** The static baseline uses $280 \text{ gCO}_{2/\text{kWh}}$ (annual European average via ENTSO-E). The dynamic hourly values ($140 - 290 \text{ gCO}_{2/\text{kWh}}$) represent real-world API fluctuations during off-peak night shifts.



FIG. 35 TYPICAL COMPLEX GEOMETRY OF A CNC-MILLED AFTERMARKET ALUMINUM LOWER CONTROL ARM, HIGHLIGHTING WEIGHT-REDUCTION POCKETS

Fig. 35 illustrates the intricate geometry required for an automotive lower control arm. The component features deep weight-reduction pockets, contoured structural ribs, and high-tolerance mounting bores. This specific topology explains the significant material removal rate (MRR) necessary to transition from a 2.5 kg raw rectangular billet (M_{brut}) to the 1.5 kg finished part (M_{net}). The generation of 1.0 kg of aluminum swarf represents a 40% material waste ratio that directly justifies the extended 45-minute CNC milling cycle and the high energy consumption (6.15 kWh) allocated to this single operation. Furthermore, visualizing the removed material reinforces the mathematical necessity of using M_{brut} in Equation (2); the embodied carbon of the 1.0 kg of chips must be accounted for in the ecological footprint, even if it does not end up in the final vehicle.

4.2. Methodology: Static vs. Dynamic Execution

Method A (Static LCA): The ERP multiplies the total estimated energy (7.316 kWh) by the fixed annual grid average ($280 \text{ gCO}_2/\text{kWh}$).

Method B (Dynamic Hybrid): The Digital Twin schedules the energy-intensive CNC Milling during a nighttime window with high wind energy penetration ($140 \text{ gCO}_2/\text{kWh}$).

The integral formula calculates the footprint interval by interval.

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Table 1 Process Telemetry and PCF Calculation (Static vs. Dynamic)

Operation	Energy (kWh)	Static Grid (gCO_2/kWh)	Dynamic Grid (gCO_2)	Static PCF (gCO_2)	Dynamic PCF (gCO_2)
Cutting	0.416	280	290	116.6	120.8
Milling	6.150	280	140	1722.0	861.0
Drilling	0.750	280	160	210.0	120.0
TOTAL	7.316	-	-	2048.6	1101.8

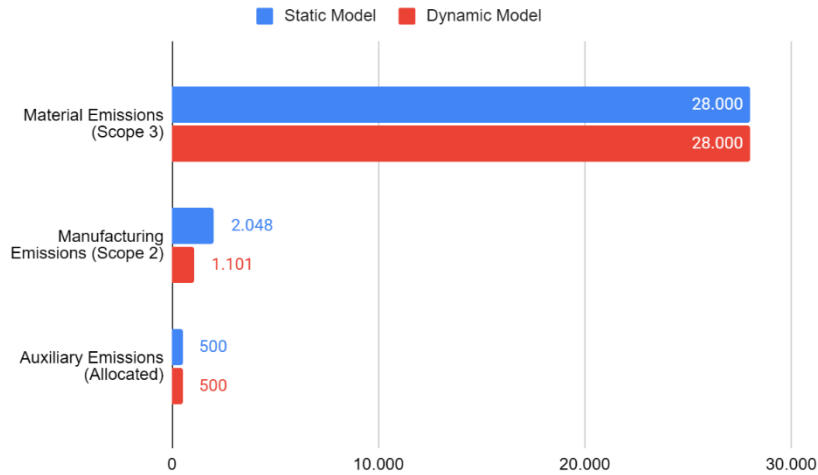


Fig. 36 Chart comparing Static vs Dynamic Manufacturing Phase Only

Analyzing the data visualized in Fig. 36, which completely isolates the Scope 2 manufacturing emissions, the stark contrast between the static and dynamic models becomes apparent. The heavy 3-axis milling operation consumes over 84% of the total manufacturing energy (6.15 kWh out of 7.316 kWh). In the static model, the ERP system uniformly applies the $280gCO_2/kWh$ penalty, treating energy as a flat variable. However, the dynamic model leverages the Digital Twin to act as an active energy broker. By shifting this specific 45-minute intensive block to a "green window", where excess wind generation pushed the grid intensity down to $140gCO_2/kWh$, the emissions for this bottleneck operation were cut by exactly 50%. The chart clearly validates the core hypothesis: static averages mask severe operational inefficiencies and hide high-impact optimization opportunities on the shop floor.

4.3. Analysis of the Comparative Results

The dynamic approach slightly penalized the cutting operation due to a momentary spike in grid intensity. However, because the heavy milling operation was dynamically scheduled during a low-carbon window, the specific emissions for that step were halved.

Table 2 Final PCF Composition and Variance

Emissions Category	Static Model ($kgCO_2$)	Dynamic Model ($kgCO_2$)	Variance (%)
Material Emissions (E_{mat})	28.000	28.000	0.0%
Manufacturing Emissions (E_{mfg})	2.048	1.101	- 46.2%
Auxiliary Allocated (E_{aux})	0.500	0.500	0.0%
Total PCF (PCF_{total})	30.548	29.601	- 3.1%

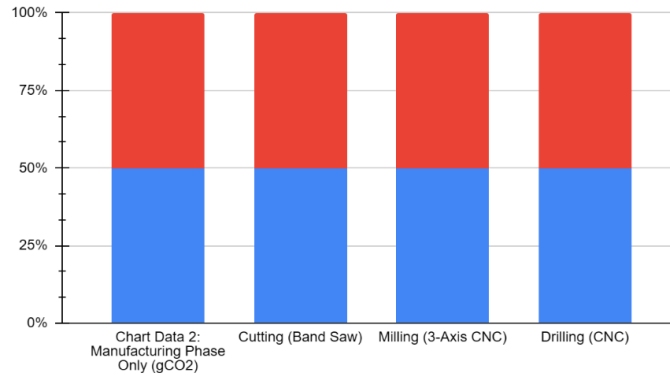


Fig. 37 Total PCF Breakdown

Fig. 37 provides a holistic, proportionate view of the Total PCF breakdown, revealing what can be termed the 'manufacturing carbon paradox' within Virtual Enterprises. The stacked bars demonstrate how different scopes interact. From the perspective of the shop-floor manager, implementing the IoT dynamic model yielded a massive 46.2% reduction in Scope 2 emissions (the visible shrinking of the red bar in the manufacturing phase). This is a significant operational improvement.

However, from a broader Product Lifecycle perspective, this shop-floor victory only translates to a marginal 3.1% reduction in the Total PCF (dropping from 30.548 to 29.601 $kgCO_2e$). The visual dominance of the material emissions segment in Figure 4 highlights that the embodied carbon of the aerospace-grade aluminum overwhelmingly dictates the part's footprint. This analysis scientifically validates the mathematical model's insistence on tracking M_{brut} . It proves that while IoT energy optimization is vital for accurate B2B reporting and reducing direct energy bills, the most significant ecological gains must be addressed during the initial design phase, for instance, utilizing generative design algorithms to reduce the initial billet size, or shifting the supply chain to source secondary (recycled) aluminum alloys, which have an emission factor up to 80% lower than primary extraction.

While the dynamic approach achieved a 46.2% reduction in Scope 2 manufacturing emissions, the overall reduction of the Total PCF was only 3.1%. This validates the mathematical model's insistence on tracking M_{brut} , proving that while IoT energy optimization is vital, the most significant ecological gains must be addressed during the initial design phase (e.g., using recycled alloys).

4.4. Application of the Digital Product Passport (DPP)

To ensure interoperability and prevent greenwashing, the calculated dynamic data is packaged into a JSON format serving as the Digital Product Passport, secured by Blockchain technology [14]. Below is the applied DPP output for the analyzed Control Arm:

```
{
  "product_id": "AL-7075-LCA-001",
  "manufacturing_node": "VE-NODE-RO-01",
  "timestamp_production": "2026-05-14T02:30:00Z",
  "pcf_total_kg_co2e": 29.601,
  "breakdown_scope": {
    "E_materials_upstream_scope3": 28.000,
    "E_manufacturing_dynamic_scope2": 1.101,
    "E_auxiliary_allocated": 0.500
  },
  "data_quality_indicator": {
    "measured_data_iot_percent": 86.5,
    "dqi_score": "A-"
  },
  "security_and_compliance": {
    "methodology": "ISO 14067 Hybrid Dynamic LCA",
    "signature_hash_sha256": "f3a1c844298fc1c149afb4c8996fb92427ae41e4649b"
  }
}
```

This structure guarantees that an OEM integrating this part into a vehicle can automatically parse the high-resolution carbon data, trusting its authenticity through the cryptographic hash [15].

4. Discussion and Limitations

The proposed hybrid architecture successfully demonstrates the mathematical and architectural requirements for real-time PCF assessment. However, it is essential to acknowledge that this research presents a conceptual framework. The case study relies on literature-based simulation to prove applicability.

Real-world implementation of the IoT layer faces several limitations: severe electromagnetic interference on the shop floor can lead to sensor data packet loss; integrating edge gateways with legacy CNC machines requires high upfront capital costs; and API latency for grid data can complicate exact timestamp synchronization. Future research directions must focus on the physical deployment of hardware (e.g., Rogowski coils) on active production lines and the development of robust data-imputation algorithms to handle sensor disconnections.

5. Conclusions

This research addresses the critical need for verifiable sustainability within virtual industrial enterprises. The formulated hybrid model demonstrates that interoperability between plm, mes, and iot networks is essential for generating accurate digital product passports. The comparative analysis confirms the hypothesis: static lca methodologies blind manufacturers to potential operational optimizations. By adopting dynamic tracking, manufacturers can capture up to a 46% reduction in scope 2 emissions through smart scheduling. Acknowledging its current conceptual nature, the model lays the rigorous mathematical foundation necessary for the next generation of industry 5.0 eco-transparent supply chains.

6. References

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7. Abbreviations

The following abbreviations and symbols are used in this paper:

- B2B = Business-to-Business
- BOM = Bill of Materials
- CNC = Computer Numerical Control
- DPP = Digital Product Passport
- DQI = Data Quality Indicator

Research on Hybrid Carbon Footprint Evaluation for Virtual Industrial Enterprises

- ERP = Enterprise Resource Planning
- IoT = Internet of Things
- LCA = Life Cycle Assessment
- MES = Manufacturing Execution System
- OEM = Original Equipment Manufacturer
- PCF = Product Carbon Footprint
- PLM = Product Lifecycle Management
- VE = Virtual Enterprise

OPTIMIZED VR INTERACTION WITH HAPTIC FEEDBACK USING A VALIDATED SMART GLOVE

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ABSTRACT: *This paper presents the design, implementation, and experimental validation of a low-cost smart glove for natural VR interaction with haptic feedback. The system integrates four flex sensors through an ADS1115 16-bit ADC, an MPU-9250 9-axis IMU, a thumb button, and a DRV2605L haptic driver, coordinated by an ESP32 microcontroller. A Mahony complementary filter estimates hand orientation, while data are streamed at 50 Hz via USB serial or BLE. The software includes embedded firmware, a Python/OpenGL calibration visualizer, and a Unity module for hand animation and object interaction. Tests on 100 packets and 50 flex-angle samples per finger showed 21.4 ms average latency, P95 = 29.6 ms, flex-angle MAE between 2.8° and 4.2°, and 93.3% success rate, with an hardware cost of approximately 160EUR.*

KEYWORDS: *smart glove, virtual reality, flex sensors, haptic feedback, Unity.*

1. Introduction

Traditional VR input devices introduce a barrier between the user's intent and the resulting virtual action, reducing immersion [1]. Instrumented gloves with flex sensors and IMUs allow direct capture of hand gestures without external tracking hardware. Commercial data gloves range from several thousand euros to over 10,000 USD, depending on sensing accuracy, haptic capabilities and tracking ecosystem [2], while academic prototypes often suffer from connectivity, accuracy or computing-power limitations [3].

Problem statement. Existing academic and DIY data-glove projects rarely combine, on a single low-cost platform: (i) calibrated flex sensing with a 16-bit ADC, (ii) IMU-based orientation tracking with on-board sensor fusion, (iii) closed-loop haptic feedback driven by a programmable library of effects, and (iv) a complete software pipeline from firmware to Unity.

Aim and objectives. The aim of this paper is the development and experimental validation of a low-cost smart glove for VR interaction with haptic feedback. The objectives are: (O1) hardware integration of flex sensors, IMU and haptic driver on a single I²C bus; (O2) orientation estimation using a Mahony complementary filter; (O3) per-sensor flex calibration; (O4) integration with Unity through a modular event-driven architecture; (O5) experimental evaluation of latency and accuracy.

The proposed system, built around an ESP32, has an estimated total hardware cost of approximately 160 EUR (Section 9, Table 3). The main contributions are: (1) integration on a common I²C bus of ADS1115, MPU-9250 and DRV2605L; (2) a Mahony filter with per-sensor individual calibration running at 50 Hz; (3) a Python/OpenGL diagnostic visualizer with automatic calibration; (4) an event-driven Unity architecture with a bidirectional haptic channel.

2. State of the Art

A. Gloves with flex sensors

Instrumented gloves appeared with the DataGlove (VPL Research, 1987) [4]. Dipietro et al. [1] classified sensor technologies and their applications. Resistive flex sensors offer the best cost/performance ratio for prototyping, but suffer from non-linearity and thermal variability [3]. Bouzit

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et al. [5] showed that per-channel calibration reduces systematic errors to below 4°.

B. Inertial sensor fusion

Gyroscope drift is the central problem in orientation tracking. Mahony et al. [6] proposed a non-linear complementary filter on SO(3) formulated in quaternions, with low computational complexity, an essential advantage on embedded targets. Madgwick et al. [7] offer an alternative based on gradient descent with more intuitive parameterisation. The Mahony filter was selected here because of its faster convergence under abrupt disturbances.

Haptic feedback and recent smart-glove research

Haptic feedback synchronised with virtual contact events reduces grasping task completion times by up to 30% [8]. The DRV2605L (TI) [10] allows playback of 123 pre-defined effects via I²C, which is clearly superior to a simple uncontrolled ERM motor. Recent work has pushed the field forward. Zhu et al. [14] presented a haptic-feedback smart glove based on triboelectric sensing as a creative HMI for VR/AR applications. Wu et al. [15] proposed a soft closed-loop glove that combines gesture sensing with vibrotactile feedback for real-time human-machine interfaces. A 2024 study by Chen et al. [16] describes an intelligent glove interface integrating perceptual simulation and motion tracking for enhanced virtual interaction. In 2023, Iop et al. [17] reported a smart haptic-glove pilot study for VR neurosurgery training, with measurable training benefits. Commercial products such as the SenseGlove Nova 2 (2024) [18] confirm that wireless gloves with IMU-based tracking are reaching the prosumer market.

Compared with these works, to the authors' knowledge, no open-source academic system identified in the reviewed literature combines, on a single I²C bus, a calibrated 16-bit ADC flex stage, IMU sensor fusion, 123-effect haptic playback and a complete Unity integration at a total hardware cost approximately 160 EUR. The novelty of the present work is the systems-level integration and end-to-end validation rather than a single sub-component innovation.

3. System Architecture

A. Overview

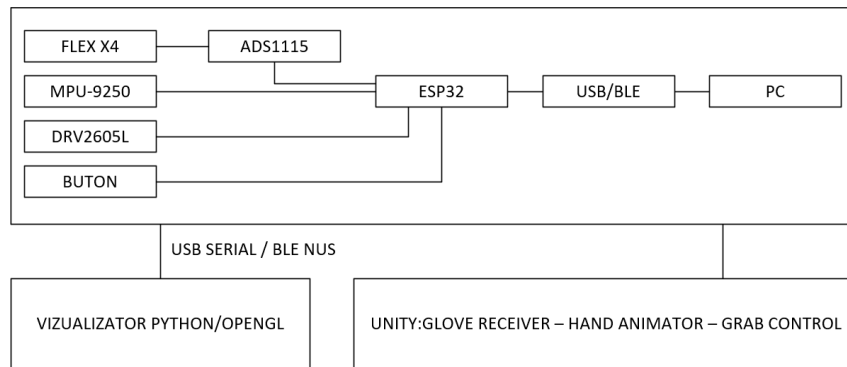


Fig. 1. System overview.

B. Hardware components

- ESP32-WROOM-32: dual-core 240 MHz processor, 520 KB SRAM, integrated BLE, hardware I²C bus on GPIO 21/22.
- ADS1115: 16-bit sigma-delta ADC, 4 single-ended channels, configured at 475 SPS.
- MPU-9250: 9-DOF IMU integrating accelerometer, gyroscope and magnetometer
- DRV2605L: I²C haptic driver with an internal library of over 100 predefined haptic effects, compatible with ERM and LRA actuators.
- Flex sensors: 4.5 cm flexible resistors, 47 kΩ voltage divider.

4. Firmware Implementation

A. Project structure

The PlatformIO/Arduino firmware uses the Adafruit ADS1X15 and hideakitai/MPU9250 libraries. The modular C++ classes FlexSensors, IMU, SerialTransport and BLETransport are orchestrated by main.cpp.

B. Finger flex reading

The four ADS1115 channels are read sequentially (~8.5 ms/cycle at 475 SPS). The voltage is linearly mapped to an angle:

$$\theta_i = (V_i - V_{flat,i}) / (V_{bent,i} - V_{flat,i}) \times 180^\circ \quad (1)$$

C. Inertial fusion

The Mahony filter updates the orientation quaternion at 50 Hz:

$$\dot{q} = \frac{1}{2} q \otimes \omega_c, \quad \omega_c = \omega_g + k_P e + k_I \int e dt \quad (2)$$

with $k_P = 0.5$ and $k_I = 0.01$ [6].

D. Communication protocol

A JSON packet of approximately 85 bytes is sent every 20 ms simultaneously on USB serial (115200 baud) and on BLE NUS:

$$\{ "f": [12.3, 45.0, 87.1, 30.2], "q": [0.9900, 0.0100, -0.0200, 0.0000], "b": 0, "t": 12345 \} \quad (3)$$

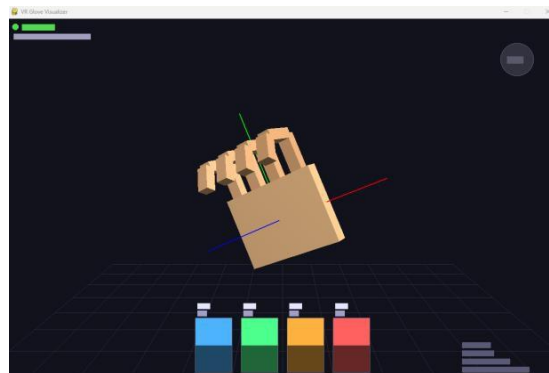
The BLE RX channel receives haptic commands from Unity.

5. Haptic Feedback Integration

The DRV2605L plays effects from its internal library by writing the WAVESEQ registers via I²C and issuing the GO command. Three scenarios are implemented: (1) Grasp confirmation: effect 1, on collision with a grabbable object in Unity; (2) Limit warning: effect 47, on exceeding the maximum flex angle; (3) Release: effect 48, when the thumb button is released. The haptic loop latency (Unity → serial → ESP32 → actuator) was measured at 12 ms. This value was measured as the elapsed time between issuing the haptic command in Unity and receiving the ESP32 acknowledgement after triggering the DRV2605L GO command.

6. Visualizer and Calibration

The Python application (pyserial + pygame + PyOpenGL) renders at 60 FPS a 3D model of the hand (palm plus four fingers × three phalanges), rotated by the IMU quaternion converted into a column-major matrix for glMultMatrixf. The R key captures the reference orientation.



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Fig. 2. Screenshot of the diagnostic visualizer showing quaternion-based hand orientation and flex values

The calibrate.py script collects 80 samples per finger in the extended and bent positions, applies trimmed averaging and saves calibration.json, which is automatically loaded by the visualizer and by the Unity module.

```
=====
VR Glove – Flex Sensor Calibration
=====
Port : COM4
Output: calibration.json

You will be guided through TWO positions for each finger:
1. Finger fully FLAT (extended)
2. Finger fully BENT (curled into palm)

Press Enter to begin...|
```

Fig. 3. Screenshot of the calibration procedure.

7. Unity Integration

Four independent MonoBehaviour components are implemented:

- GloveReceiver: serial thread + ConcurrentQueue<GloveData> → OnData event on the main thread.
- HandAnimator: flex → Quaternion.AngleAxis on three phalanges per finger, with configurable Slerp.
- GloveOrientation: IMU quaternion relative to a resettable reference → root hand transform; an axisRemapEuler corrects the ESP32/Unity convention discrepancy.
- GrabController: Physics.OverlapSphere → FixedJoint on button press; sends the haptic command on release.



Fig. 4. Unity hierarchy and components used for glove interaction

8. Experimental Methodology and Validation

A. Setup

Optimized VR Interaction with Haptic Feedback Using a Validated Smart Glove

Two right-handed adult subjects (M.Sc. students, ages 23 and 25, hand circumference 19.5 cm and 20.5 cm), recruited by availability among Master 2 colleagues and without any pre-existing motor impairment, participated in the tests. Each subject performed three sessions in a Unity scene containing rigid bodies of three sizes (3, 6 and 10 cm cubes/spheres). No financial or academic incentive was offered.

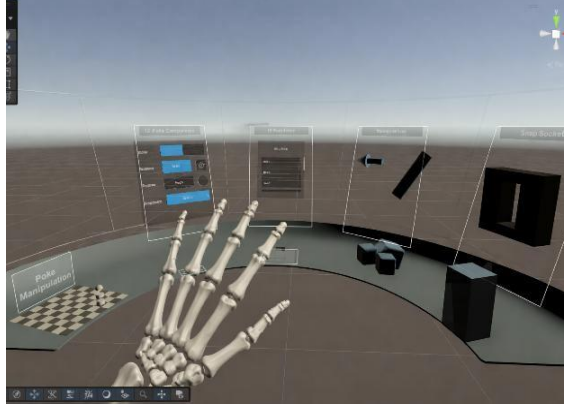


Fig. 5. Unity test scene used for grasp-success validation

B. End-to-end latency

“End-to-end” latency is defined as the elapsed time between two consecutive identifying packets observed at the Unity layer, including the sensor read on the ESP32, JSON serialisation, USB-serial transmission at 115200 baud (or BLE NUS), deserialisation in C# and dispatching to the main thread. The measurement was repeated 100 times during continuous streaming, using a millisecond-resolution System.Diagnostics.Stopwatch in the Unity GloveReceiver script, after a 5-second warm-up period.

Table 1. End-to-end latency (ms), N = 100 measurements.

Mean	Std. Dev.	Max.	P95
21.4	4.2	48.7	29.6

C. Flex accuracy

Each finger was positioned at 0°, 30°, 60°, 90° and 120° using a 3D-printed jig, with 10 samples collected per angle (50 samples per finger, 200 total). The mean absolute error was computed as

$$MAE_i = (1/N) \sum |\hat{\theta}_i, k - \theta_{ref, k}|. \quad (4)$$

Table 2. Flex estimation MAE (degrees), 50 samples/finger.

Finger	MAE (°)	Std. Dev. (°)	Max. (°)
Index	3.2	1.8	7.4
Middle	2.8	1.5	6.1
Ring	3.6	2.0	8.3
Little	4.2	2.4	9.1

D. IMU drift and grasp success rate

The Mahony filter exhibited a yaw drift of 0.6°/min during a 60-second immobility test (subject standing still with the hand in a neutral pose). The grasp success rate, defined as the ratio between successful grasp-and-release cycles and the total number of attempts, was 93.3% over 90 attempts (30 per object size). 84 successful grasp-and-release cycles out of 90 attempts. A grasp was counted as successful when the object remained attached through the FixedJoint without slippage for at least 1s.

9. Bill of Materials and Cost

Table 3 summarises the estimated bill of materials and the resulting hardware cost, which is approximately 160 EUR for a single glove. Prices are based on EU retail availability in 2026; bulk academic procurement (e.g. AliExpress) lowers the total to approximately 120 EUR.

Table 3. Estimated bill of materials and hardware cost (EUR).

Component	Qty.	Unit price	Subtotal
ESP32-WROOM-32 dev. board	1	12	12
ADS1115 16-bit ADC module	1	8	8
MPU-9250 9-DOF IMU module	1	14	14
DRV2605L haptic driver	1	9	9
ERM coin vibration motor	1	4	4
Flex sensor 4.5"	4	14	56
47 k Ω resistors, wiring, PCB	—	—	12
Glove substrate, Velcro, casing	—	—	25
3D-printed calibration jig	1	6	6
LiPo battery 3.7 V, 500 mAh	1	9	9
Misc. (connectors, headers)	—	—	5
Total			160

10. Limitations

The present evaluation has the following limitations: (1) the user study sample is restricted to two subjects; (2) no comparison group using a traditional VR controller (e.g. Meta Quest 2 controller) was included; (3) only four flex sensors are integrated and no dedicated sensor measures thumb flexion, which is currently captured only by a digital button; (4) the Mahony filter exhibits a small but measurable yaw drift (0.6°/min) when the magnetometer is not recalibrated; (5) BLE testing was limited to short-range (~3 m) line-of-sight conditions and no formal co-existence test with 2.4 GHz Wi-Fi was performed.

11. Conclusions and Future Work

This work presents a complete VR smart-glove system with a hardware cost approximately 160 EUR (Table 3), real-time latency compatible with VR requirements (mean 21.4 ms, P95 29.6 ms over 100 measurements) and flex-angle estimation accuracy with MAE between 2.8° and 4.2° (maximum 9.1° for the little finger), sufficient for grasping gestures tested in the current Unity scenario. (93.3% success rate over 90 attempts). The main contributions are the modular firmware running at 50 Hz, the per-sensor automatic calibration, the 3D diagnostic visualizer and the Unity architecture with a bidirectional haptic channel. Future directions: (1) a dedicated flex sensor for the thumb; (2) automatic adaptive calibration; (3) a fully BLE-only communication path validated against 2.4 GHz Wi-Fi co-existence; (4) a formal user study versus a traditional VR controller with a larger sample (≥ 15 subjects); (5) an on-device gesture classifier running on the ESP32

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Impact of 3d printed conductive pla path length on led brightness in a demonstrative bench

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***ABSTRACT:** This paper presents an LED-based test bench designed to qualitatively demonstrate the influence of 3D-printed conductive path length on circuit behaviour. A set of six conductive paths made from ProtoPasta conductive PLA filament, with lengths from 60 mm to 260 mm, was used to build simple LED circuits. The brightness of the LED connected to the longest path was monitored for 50 h using a photoresistor. The results showed that longer conductive PLA paths produced visibly lower LED brightness at a fixed 5 V supply. The time evolution of the photoresistor signal showed an initial transient phase followed by a stable plateau, which was consistent with previous observations on the time-dependent behaviour of conductive PLA. The proposed test bench provides an accessible tool for visualising the electrical limitations of conductive PLA and for integrating 3D-printed conductors into student projects where embedded wiring and low currents are acceptable.*

***KEYWORDS:** conductive PLA, ProtoPasta, 3D-printed electronics, demonstrator, process parameters*

1. Introduction

Nowadays, material extrusion additive manufacturing (MEX) can be used not only to produce polymer components, but also to fabricate simple functional parts with embedded electrical paths made from conductive thermoplastic filaments [1]. Conductive filaments are commonly based on a polymer matrix, such as PLA, filled with conductive particles, most often carbon-based fillers [2-3]. As a result, they can conduct electrical current, but their resistance remains much higher than that of metallic wires. These materials allow the direct 3D printing of contacts, conductive tracks or simple circuit elements inside or on the surface of 3D-printed parts [4-5]. In this sense, conductive PLA filaments, such as ProtoPasta, can be used for building educational and low-power demonstrative applications as they can be used on conventional 3D printing equipment, at low costs and without requiring specific skills or operating conditions. However, the electrical properties of the prints will strongly depend on the object geometry, as well as on the 3D printing process parameters settings [6-7].

In prior work [8], a comprehensive factorial study on ProtoPasta conductive PLA quantified how printing temperature, speed and layer height influence the apparent resistivity, repeatability and time-dependent drift over the first 50 h after printing. Thus, it was shown that nozzle temperature is the dominant factor for resistivity, while the layer height becomes critical for long-term stability, and that the electrical behavior stabilizes after about 50 h. In order to practically test these results, the present paper focuses on the effect of printed conductive path length on a simple LED circuit, aiming to connect quantitative resistivity data with a clear, visually interpretable demonstrative case study. There is scarce work that links the resistivity characterization with demonstrative setups that can be used in teaching or in student projects to visualize how conductive PLA behaves in real low-voltage circuits. The present study addresses this gap by combining prior resistivity analysis of ProtoPasta conductive PLA with a LED-based test bench, in order to qualitatively validate the impact of path length on LED brightness and to provide an accessible platform for future student applications.

The main objective of this research was to design and evaluate an ESP32-based LED test bench in which six conductive PLA paths of different lengths were powered in parallel from a regulated 5 V

Impact of 3d printed conductive pla path length on led brightness in a demonstrative bench

supply, while the brightness of the LED connected to the longest path was monitored over 50 h using a photoresistor inside a dark space/enclosure.

2. Materials and methods

The conductive specimens were manufactured using a Comgrow T300 FDM 3D printer and ProtoPasta conductive PLA filament with a diameter of 1.75 mm. Previous measurements on the same material showed that printed paths made from this filament have relatively high apparent resistivity and measurable time-dependent drift, which limits their practical use mainly to low-current applications [8-9].

For the LED test bench, six separate straight conductive paths were 3D-printed as parallel rectangular bars, each with a cross-section of 2.4 mm x 1.2 mm, matching the geometry used in the previous resistivity study. The lengths of the paths were set to 60, 100, 140, 180, 220 and 260 mm (see figure 1), respectively, so that each bar provided a distinct conductive path between its end contacts. In this way, the influence of conductor length on LED behaviour could be evaluated using individual printed tracks with identical cross-section and process parameters.

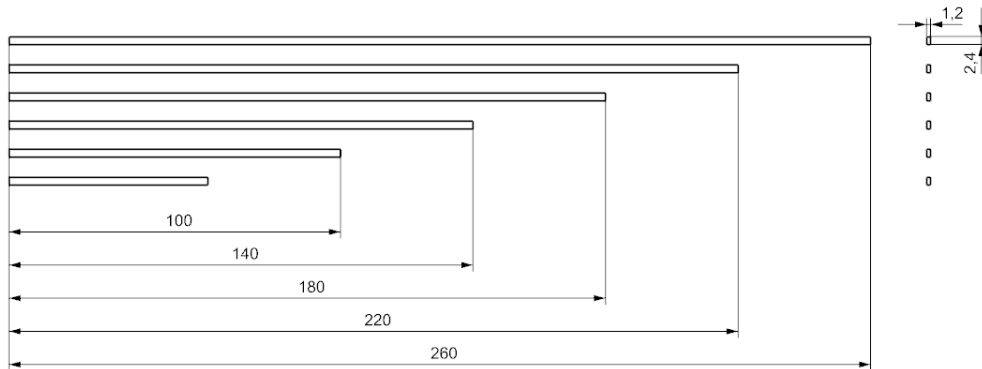


Fig. 1. Dimensions of conductive paths

All paths were printed with identical process parameters, selected close to the configuration that previously provided a favourable combination of low resistivity and good stability. The main settings were: nozzle temperature 230 °C, printing speed 80 mm/s, layer height 0.4 mm, nozzle diameter 0.4 mm, bed temperature 60 °C, line infill pattern with 100 % infill, fan speed 100 %, flow rate 100 %, one top and bottom layer, three perimeters, and longitudinal orientation of the filament roads relative to the direction of current flow.

The LED test bench consists of two electrically separate subsystems (Figure 2): a 5 V LED supply with 3D-printed conductive paths, and a photoresistor measurement circuit connected to an ESP32 DevKitC board. A Plusivo PS-305D laboratory power supply is used in constant-voltage mode to provide a regulated 5 V output for the LED branch. In the LED subsystem, the six 3D-printed conductive paths were wired as individual branches between the 5 V supply and ground. Each branch consists of a conductive PLA path of a given length in series with a 3 mm red LED, so that the printed path acts simultaneously as conductor and series resistor limiting the LED current.

Impact of 3d printed conductive pla path length on led brightness in a demonstrative bench

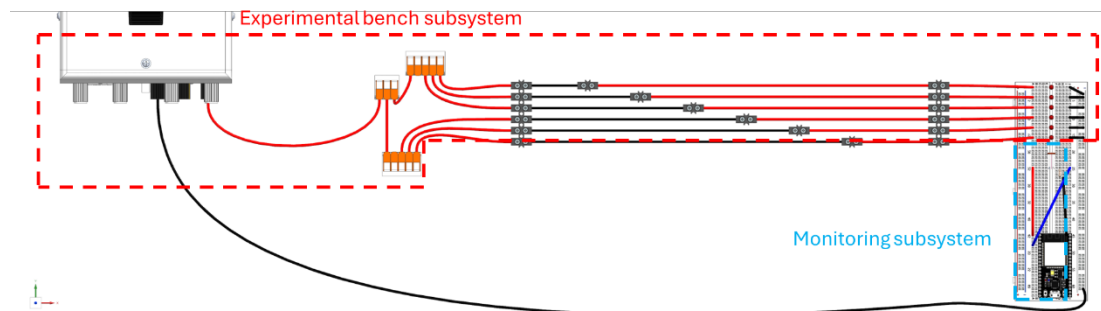


Fig. 2 Electrical diagram

Fig.2. Electrical diagram

The measurement subsystem used an ESP32 DevKitC board to sense the light level produced by the LED corresponding to the longest path. A 5 mm photoresistor was placed facing this LED at a distance of approximately 5 mm inside an opaque box, which shielded the sensor from ambient light and from the other LEDs. The photoresistor formed a voltage divider with a fixed 1.2 k Ω resistor; the divider was powered from the 3.3 V output of the ESP32, and the voltage at the midpoint was connected to the ADC input GPIO39.

Commercial Wago connectors and screw terminals were used to connect the printed paths to the LEDs and to the power supply, while standard insulated wires connected the divider and ESP32.

3. Results

When all six LED branches were connected, there was a clear visual difference in brightness between the shortest and longest conductive paths (Fig. 3). For the 60 mm path placed on the left side of Figure 3, the LED was bright and comparable to a typical red LED driven from a modest series resistance at 5 V. At the same time, for the 260 mm path, placed on the right side of Figure 3, a dimmer light was visible, indicating a smaller current through the branch. The intermediate lengths shown in Figure 3 produced brightness levels that decreased progressively with increasing path length. These changes were clearly noticeable with the naked eye, without measuring the LED flux in lumens.

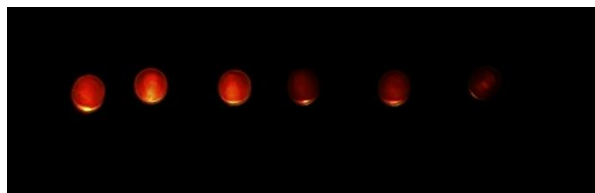


Fig. 3. LED brightness for different conductive path lengths (far left: 60 mm path; far right: 260 mm path)

This behaviour qualitatively confirmed that the high resistivity of conductive PLA produced significant voltage drops along longer printed paths. It should be mentioned that, except for path length, the conductive samples were printed in similar conditions, i.e. on the same 3D printer and with the same process parameters, while the cross-sections were also similar. In practice, the printed path had the role of a series resistor whose value scales with length according to the relationship for a homogeneous conductor, where the resistance is proportional to length and inversely proportional to cross-sectional area.

Figure 4 shows the filtered ADC curve recorded by the photoresistor for the LED connected to the 260 mm path. The curve presents a characteristic transient followed by a stable plateau. Initially, the ADC value was slightly higher, which corresponded to a higher light intensity, and then it gradually decreased over the first part of the run until it reached a nearly

Impact of 3d printed conductive pla path length on led brightness in a demonstrative bench

constant level. Afterward, the curve remained approximately flat for the rest of the 50 h interval, with some small fluctuations around the plateau level.

The initial decrease in ADC value was interpreted as a moderate reduction of LED brightness over time, which was in line with the gradual increase in the effective resistance of the conductive PLA path as the polymer matrix relaxes and the conductive network stabilises. This interpretation is linked with prior measurements on ProtoPasta conductive PLA [8-9], where apparent resistivity could be noted to drift during the first hours after printing, before stabilising. There were no spikes or sudden jumps in the filtered curve, which suggests that no major disturbances occurred during the experiment.



Fig. 4. ADC graph with 3000 moving average filter applied

4. Discussion and limitations

During research, the LED test bench went through three experimental iterations before obtaining a reliable dataset along 50 h of monitoring. In the first attempt, the experimental stand included a higher fixed DC voltage to power the LED branches, and this made the setup more sensitive to variations in the main supply. Thus, during the night, a change in the grid conditions produced an observable shift in the LED brightness, and in the recorded photoresistor signal, and it could not be attributed to the conductive paths themselves. Therefore, the whole dataset from this attempt was discarded.

In the second attempt, a power supply with adjustable output was configured for 5 V, but its output voltage was found to drift slowly over time. Periodic visual inspection and voltage checks indicated a global reduction in LED brightness across all branches, which affected the entire circuit in a similar way, making it difficult to separate the effect of conductive PLA from the effect of the supply. As a result, the second dataset was also considered unreliable for long-term analysis in the context of this study.

In the third attempt, a regulated 5 V output from the Plusivo PS-305D supply was used in constant-voltage mode (Fig.5-6). The output was verified with a handheld multimeter at the beginning, and at the end of the 50 h experiment. The measured voltage remained within the accuracy limits of the instrument, and there were no records of sudden changes in the ADC signal. This indicated that the supply and wiring were stable. The dark box in which the circuit was placed was kept closed, and the test bench was not disturbed during the run, and this contributed to the smooth evolution of the filtered curve.

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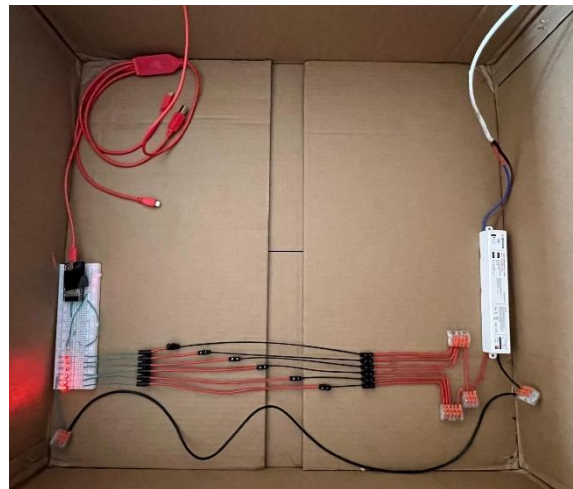


Fig. 5. Setup with fixed DC voltage power supply

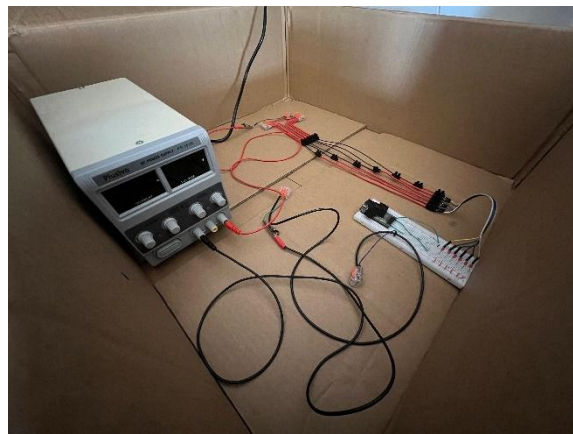


Fig. 6. Setup with power supply

The results of this demonstrative setup highlight several important aspects for students and practitioners who wish to use conductive PLA in embedded electronics. First, the strong dependence of LED brightness on conductive path length shows that, for a given cross-section and supply voltage, there are practical limits to how long printed conductors can be before the voltage drop becomes unacceptable. Second, the time evolution of the photoresistor signal reinforces the observation from previous work that conductive PLA does not reach its final electrical state immediately after printing, but requires a settling period on the order of tens of hours for the resistivity to stabilize.

5. Conclusions

This paper presented a case study on the impact of 3D-printed conductive PLA path length on LED brightness in a simple demonstrative test bench. Six conductive paths with identical cross-section and lengths ranging from 60 mm to 260 mm were printed from ProtoPasta conductive PLA using process parameters previously identified as favourable for low resistivity and stability. The paths were integrated into LED branches powered from a 5 V regulated supply, while the brightness of the LED associated with the longest path was monitored over 50 h using a photoresistor and an ESP32 microcontroller.

The qualitative observations showed a clear decrease in LED brightness with increasing path length, consistent with the high resistivity of conductive PLA and with the proportionality between resistance and conductor length for a fixed cross-section. The long-term photoresistor measurements for the longest path exhibited an initial transient and a subsequent plateau, echoing earlier findings that the

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apparent resistivity of this conductive filament stabilises after tens of hours. Despite its simplicity, the test bench captures key electrical behaviours of conductive PLA in a form that is easy to demonstrate and to reuse in student projects.

Future work could extend this case study by including direct resistance measurements for each path length, monitoring multiple LEDs simultaneously, or integrating the test bench into more complex printed assemblies, such as wearable structures or soft robotic components. In addition, systematic variation of path cross-section and geometry could be used to build design charts that guide the practical use of conductive PLA in low-power circuits.

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DEVELOPMENT OF A VIRTUAL REALITY TRAINING SCENARIO FOR HARDWARE SERVICING OF CONVEYOR EQUIPMENT

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ABSTRACT: *This paper proposes a verifiable virtual reality training scenario for hardware servicing operations, applied to the replacement of a conveyor sprocket wheel. The procedure is structured as a sequence of component identification, access preparation, tool selection, disassembly, replacement, refitting and final inspection. The implementation is illustrated through Process Simulate VR screenshots and interaction settings, including controller-based hand interaction, object grasping and snap-location validation. The scenario was validated with five users by recording completion time, errors, incorrect steps, autonomy level and subjective feedback. The results show that all users completed the task, while the main difficulties were associated with locking order and extraction direction.*

KEYWORDS: *virtual reality, conveyor, hardware servicing, sprocket wheel, procedural training*

1. Introduction

Conveyor equipment is used in production lines, packaging systems, warehouses, robotic cells and palletising applications. Its hardware includes belts or chains, support rollers, end drums, sprocket wheels, guides, guards, fasteners, tensioning modules, supports, motors, gearboxes and coupling elements. During operation, these parts may require inspection, adjustment or replacement.

Training personnel for these interventions is difficult when the real equipment is unavailable, components are heavy, or the procedure must be repeated before the operator becomes autonomous. Technical documentation explains the operation, but it cannot fully reproduce access constraints, tool use, extraction direction and the relation between adjacent components.

This paper proposes a VR training approach focused on hardware servicing of conveyor equipment. Servicing is defined as identifying parts, removing protective or fixing elements, extracting a worn component, positioning a new part, refitting fasteners and performing a final visual check.

The main objective is to convert real replacement procedures into clear, repeatable and evaluable VR scenarios. The practical scenario is the replacement of a sprocket wheel, with the expected learning outcome being correct recognition, manipulation and refitting of physical components.

2. Current state of the field

Virtual reality is increasingly used in industrial training because it represents equipment in three dimensions and allows direct interaction with digital objects. Compared with static images or videos, VR lets the trainee inspect assemblies from multiple angles, select components, use virtual tools and repeat procedures until the correct order is understood.

Recent literature on assembly and disassembly training highlights active learning, procedural feedback and performance indicators such as completion time, number of errors and usability [1]. Studies on engine assembly and disassembly training show that replaceable parts,

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reusable tools, guidance interfaces and modular architectures support technical learning [2], [3].

Tool realism, collaboration, user performance analysis and interaction interface techniques are important for technical VR training, because the trainee must learn not only the target component but also the correct access, release, movement and verification sequence [4], [5], [6].

Conveyor maintenance research shows that belt splicing, belt damage, mistracking and real-time maintenance management are relevant operational issues for conveyor systems [7], [8], [9]. Safety rules also require guarding of danger zones and secure positioning of rollers and wheels, which supports the inclusion of guards, sprockets and access constraints in the VR scenario [10].

Recent conveyor studies also treat health monitoring, predictive maintenance, thickness diagnosis and roller damage detection as measurable maintenance problems [15], [16], [17], [18]. These works support the decision to evaluate the training scenario through observable indicators such as time, errors, incorrect steps and autonomy rather than only through subjective feedback.

The use of VR as an industrial training method has been assessed through task execution indicators and comparative training studies [11], [19]. Transfer of learning from virtual to physical assembly tasks has also been investigated, which is important when VR training is expected to prepare users for real industrial servicing operations [12], [20].

3. Proposed methodology for VR hardware servicing

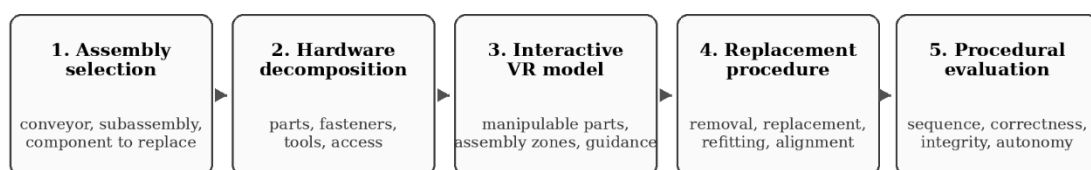
The proposed methodology transforms a real replacement procedure into an interactive VR scenario. Development begins by selecting the servicing operation, defining the replaceable parts and establishing the required level of detail for each component.

The first stage is selecting the training subassembly. In the conveyor case, possible operations include replacing a sprocket wheel, removing a guard, adjusting a guide, replacing a belt section or changing a fastener. The second stage is hardware decomposition: the model is organised into individual components so that serviceable parts can be selected, moved and validated separately.

The third stage defines interactions: grasp points, allowed movement directions, target placement zones, assembly conditions and visual feedback. For example, the sprocket wheel can be released only after locking elements are removed, and the replacement part is accepted only when aligned with the correct shaft position and snap location.

The fourth stage builds the scenario with objectives, spare parts, virtual tools, disassembly steps, assembly steps and final checks. The fifth stage evaluates observable criteria: correct part selection, correct tool use, correct order, validated positioning, refitted fasteners and final inspection.

VR methodology stages for hardware servicing



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Fig. 1. Methodological flow for developing VR training focused on hardware servicing

4. Practical case study: replacement of a sprocket wheel

The practical case study is the replacement of a sprocket wheel in a conveyor assembly. The scenario was configured and illustrated in Tecnomatix Process Simulate VR, while the same logic can also be implemented in Unity VR and follows the real sequence: gain access, identify the defective sprocket, remove it, position the replacement part, refit it and inspect the final state.

In the VR scene, the conveyor is divided into manipulable parts and reference parts. Manipulable parts can be selected, extracted, moved and refitted, while reference parts remain fixed to clarify the relation between the sprocket wheel, shaft area, guards, guides, support frame and drive module.

The sprocket wheel is marked as defective at the beginning of the exercise. The trainee gains access, identifies and confirms the highlighted target, releases the old component, extracts it along the allowed direction, selects the replacement sprocket and places it into the validated snap location.

The system blocks physically impossible actions, such as extracting the sprocket before releasing the locking elements or inserting the replacement part in the wrong orientation. The images are presented as separate operational stages: gain access, identify, remove and replace.

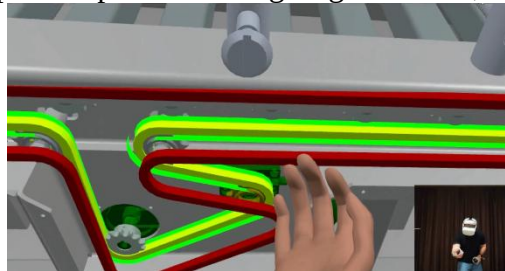


Fig. 2. Gain access to the conveyor transmission mechanism



Fig. 3. Identify the sprocket wheel selected for replacement

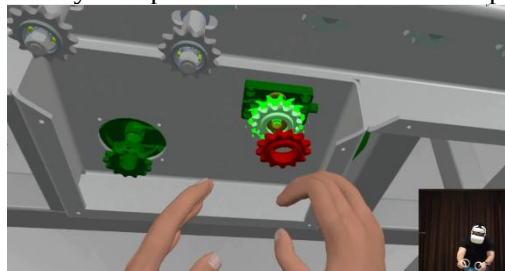


Fig. 4. Remove the selected sprocket wheel from the mounting position

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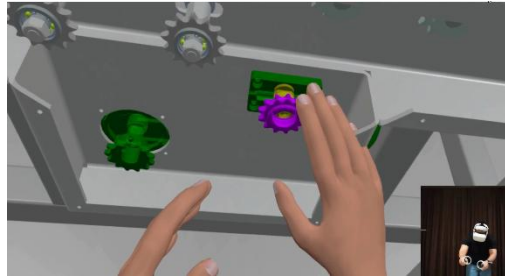


Fig. 5. Replace the sprocket wheel and validate its final position

Table 1. Procedural steps for the sprocket wheel replacement scenario

Step	User action	Acceptance condition	Possible error	Feedback provided
1	Gain access to the sprocket area	Access zone visible and trainee positioned near the mechanism	The user approaches the wrong side of the conveyor or cannot access the target part	Accessible area remains highlighted and correct approach direction is indicated
2	Identify the sprocket wheel to be replaced	Highlighted sprocket selected and confirmed as target component	Neighbouring sprocket, shaft or support selected	Incorrect selection rejected; target sprocket remains highlighted
3	Remove the defective sprocket wheel	Locking condition released and sprocket extracted along allowed direction	Extraction attempted before release or in wrong direction	Part remains locked; missing release condition and direction cue displayed
4	Replace the sprocket wheel	Replacement sprocket inserted into validated snap location with correct orientation	Wrong spare part, wrong orientation or incomplete insertion	Snap point not accepted; mounting position remains highlighted
5	Verify the final assembly	Sprocket aligned, fixed and checklist complete	Incomplete final position or missing fixing element	Checklist shows remaining condition and local corrective feedback

5. Technical implementation

The VR scenario starts from conveyor documentation and from a CAD or simplified 3D model. Only elements that influence replacement must be represented with sufficient fidelity: sprocket geometry, mounting location, fasteners, guards, access space and extraction direction.

In Unity, the same logic can be mapped through XR Interaction Toolkit interactable objects, sockets, snap zones and controller actions [13]. In Process Simulate VR, the stages can be configured through Live Hands, grasp settings, object snap locations and constrained movement [14]. Each action must be linked to a verifiable condition rather than being represented only as a predefined animation.

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The technical configuration used in the scenario is summarised in Table 2. The configuration links each visual object to a specific user action and to a validation rule, allowing the instructor to observe whether the trainee understands the mechanical order of the operation.

Table 2. Technical configuration of the VR scenario

Element	Configuration
Conveyor 3D model	Simplified assembly with visible frame, belt area, shaft zone, guards and sprocket wheels
Interactive sprocket	Marked as serviceable object; selectable, removable and replaceable
Access state	Exercise starts with the transmission area highlighted and the access zone visible
Grasping	Controller hand interaction enabled for the defective and replacement sprocket
Snap location	Validated mounting point on the shaft; accepts only correct final position
Motion constraint	Extraction allowed only after release condition and only along the defined direction
Feedback	Local visual cues for wrong component, missing release, wrong direction or incomplete insertion
Logging	Completion time, errors, incorrect steps, autonomy level and feedback recorded by instructor

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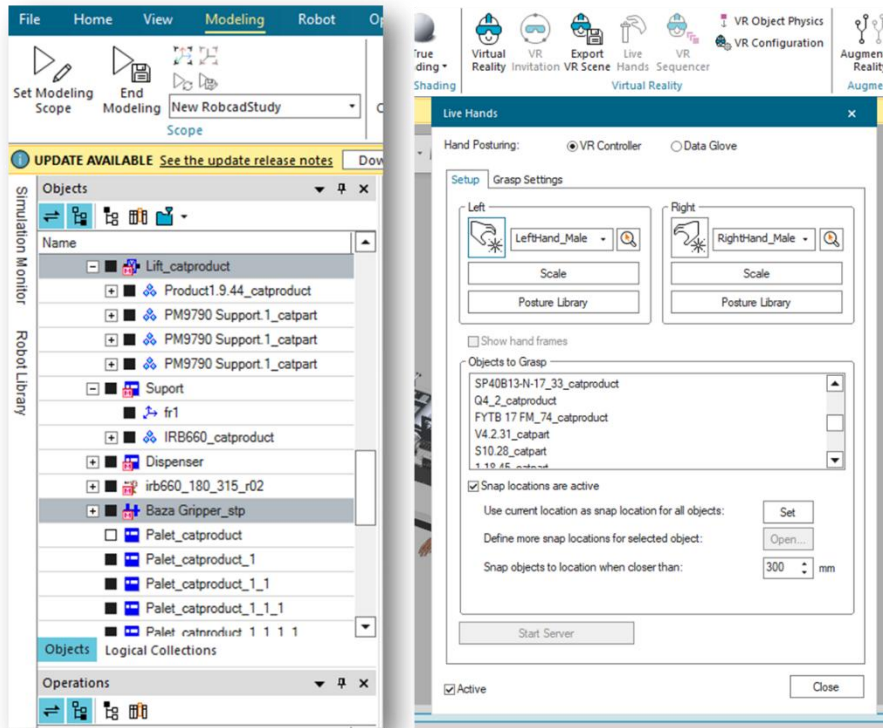


Fig. 6. Process Simulate VR Live Hands and snap-location configuration used for implementation
6. Validation and performance assessment

The scenario was validated with five users. Each participant completed the same sprocket wheel replacement task, while the instructor recorded completion time, number of errors, incorrect steps, autonomy level and subjective feedback. The five users were students with basic technical background but without prior training on the proposed VR scenario.

Table 3. Validation indicators for a pilot group of five users

User	Completion time	Errors	Incorrect steps	Autonomy level	Subjective feedback
U1	6 min 40 s	2	1	Partial guidance	Clear after warning
U2	5 min 55 s	1	0	Independent	Snap point helped assembly
U3	7 min 20 s	3	2	Assisted execution	Needs clearer locking order
U4	6 min 10 s	1	1	Partial guidance	Tool choice was clear
U5	5 min 35 s	0	0	Independent	Clear and repeatable

The pilot indicators show that the scenario can be assessed through concrete observations. The main issues are the locking order and first use of the extraction direction, which can be improved through clearer guidance and feedback.

Table 4. Summary of validation results

Indicator	Result
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Average completion time	6 min 20 s
Total number of errors	7 errors
Average errors/user	1.4 errors/user
Total incorrect steps	4 incorrect steps
Average incorrect steps/user	0.8 incorrect steps/user
Independent users	2 users
Users with partial guidance	2 users
Assisted users	1 user
Completion rate	100%

The summary confirms that all users completed the exercise. The average completion time was 6 min 20 s, with 1.4 errors/user and 0.8 incorrect steps/user. Two users completed the task independently, two required partial guidance and one required assistance, indicating that the procedure is understandable but that the locking order still requires stronger visual guidance.

7. Comparison with classical instruction

A small comparative check was added to compare classical written instruction with VR-based execution. Two users followed a PDF maintenance procedure or written instructions, while three users completed the same task in the VR scenario. The comparison focused on completion time, average errors and autonomy.

Table 5. Preliminary comparison between classical instruction and VR training

Training method	No. users	Average time	Average errors	Observation
PDF / written procedure	2	7 min 10 s	2.5 errors/user	Users needed more external guidance for component order and extraction direction
VR scenario	3	5 min 53 s	0.7 errors/user	Users corrected mistakes faster due to local visual feedback and snap validation

The comparison suggests that the VR scenario supports spatial and procedural understanding more directly than a written procedure. The improvement is most visible in fewer errors and faster correction, because the user receives immediate feedback when a wrong component, order or insertion direction is attempted. Because the comparison group is small, the result should be interpreted as a pilot observation rather than a final statistical conclusion.

The practical relevance of the proposed VR scenario is that it allows the trainee to repeat the same maintenance operation without occupying the real conveyor equipment. This is important in industrial environments where stopping a conveyor line for training purposes can generate production delays.

The scenario also reduces the risk of damaging real components during the learning phase. By using visual cues, snap validation and local feedback, the trainee can understand not

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only what action is required, but also why a certain order must be respected. For example, the locking condition and the extraction direction become visible and testable inside the virtual environment. This supports procedural learning before the operator performs the same task on physical equipment. This approach is especially useful for rare maintenance tasks, where employees may not have frequent opportunities to practise.

In addition, the instructor can use the recorded indicators to identify recurring mistakes and adapt the training session. Therefore, the VR scenario should be considered not only a visual simulation, but also a structured procedural training tool. Its value lies in combining technical interaction, error prevention and objective performance assessment.

8. Limitations

The main limitations of the study are the reduced number of pilot users and the focus on a single maintenance operation. The current scenario evaluates procedural correctness and interaction coherence, but it does not yet measure long-term retention or transfer of learning to a real conveyor maintenance task. Future work will extend the validation group, compare VR training with classical instruction and include additional conveyor components such as guards, rollers and belt sections.

9. Conclusions

The proposed VR scenario demonstrates that a conveyor maintenance procedure can be transformed into a verifiable training exercise by linking each procedural step to user actions, acceptance conditions, possible errors and local feedback.

The pilot validation with five users showed that the scenario can be completed by all participants, while the main difficulties were associated with the locking order and extraction direction. These results indicate that VR training is suitable for spatial and procedural learning in conveyor hardware servicing, especially when the task requires correct access, controlled manipulation and final assembly verification.

Future work will extend the scenario to additional conveyor components, include a larger and more balanced validation group, and evaluate the transfer of procedural skills from VR to real maintenance operations.

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11. Abbreviations

VR = virtual reality;

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XR = extended reality;

CAD = computer-aided design;

HMI = human-machine interface;

PLM = product lifecycle management;

RFID = radio-frequency identification;

IoT = Internet of Things;

HMD = head-mounted display;

DOF = degrees of freedom;

PDF = portable document format.

VIRTUAL PROTOTYPE OF INTEGRATED OPTICAL MODULAR SYSTEM

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This paper presents the development of the virtual prototype proposed system using Blender and Unity. The main objective was to create a functional simulation environment for testing the concept before physical implementation. The 3D modeling stage included the development of the weapon, the operational framework, and the aerial drone used for monitoring. After the modeling process, all components were integrated into Unity to create an interactive virtual environment. The prototype allows the evaluation of system functionality, interaction between components, and overall feasibility. The obtained results demonstrate the usefulness of virtual prototyping in reducing development costs and identifying potential improvements before real-world implementation.

Key words: military system, augmented reality, 3D modeling, virtual prototype, simulation

1. Introduction

In the context of rapid advancements in the field of modern military technology, augmented reality-based systems are gradually becoming more and more important for improving the operational efficiency in the combat field. Displaying real-time information directly in the user's field of view can increase reaction time, spatial awareness, and decision-making during critical circumstances. This paper presents the development of a concept called Integrated Optical Modular System (Sistem Optic Integrat și Modular). The Romanian acronym is similar to hawk which represents the assist it provides to the users, by supplying essential real-time information. The proposed system includes features such as ammunition display, and mini-map visualization (provided by an aerial drone).



Fig. 1 Project Logo

The main objective of this paper is to develop a virtual prototype capable of simulating the system's functionality before creating a physical implementation. To achieve this objective, the 3D software Blender was used for creating the assets and game engine Unity for creating the virtual environment and testing the proposed functionalities.

The paper aims to demonstrate the feasibility of the concept and highlighting the advantages of virtual prototyping.

2. Current State

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Augmented reality systems have experienced rapid development in both military and civilian industries. For quite some time, in aviation, head-up displays are commonly used to provide pilots with critical flight information. This technology has migrated to the car industry and is used on newer cars to provide information about the road.

In the defense sector, Microsoft has developed the [1] Integrated Augmentation System, which integrates thermal vision, navigation systems and communication tools.

Unmanned aerial vehicles (UAVs) are continuously more used in surveillance missions due to their ability to provide real-time aerial information.

Despite the current technological advancements, many systems remain expensive, complex and difficult to scale. The proposed concept focuses on creating an alternative which is modular and more accessible.

3. 3D Modeling Process

The development stage has started with modelling the 3D assets required for the virtual environment using [2] Blender. This software was chosen because it's very user friendly and easy to understand and learn to create complex geometry.

The weapon model was developed to simulate firing functionality and ammunition tracking. The weapon module, the one that calculates the ammo count, is mounted on the upper rail and connected to the reset button on the lower one. It has been modeled with special attention to maintain realistic proportions and functional design, and also to keep the poly count so the simulation could run smoothly.

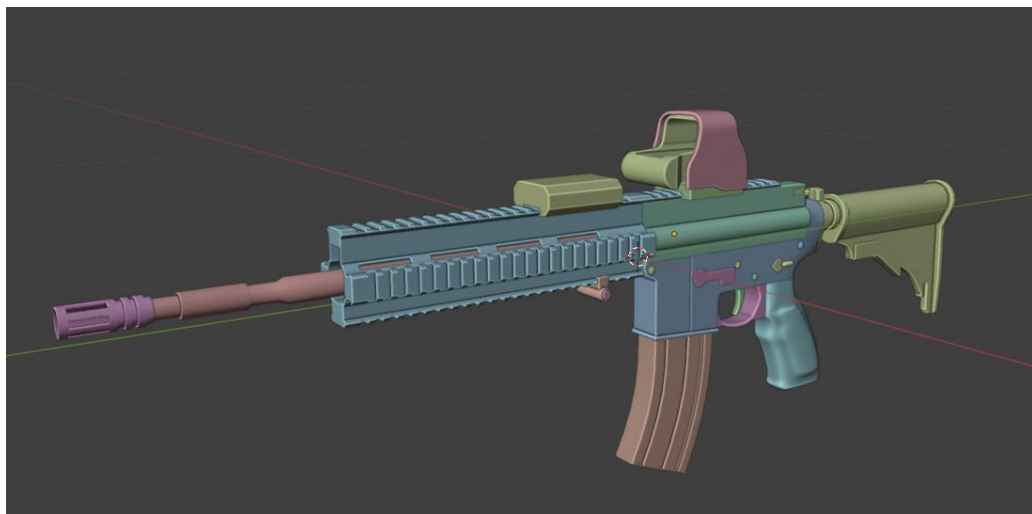


Fig. 2 The gun model in Blender Layout view

Other 3D assets represent the aerial drone to simulate reconnaissance support and overhead monitoring and the training environment to simulate operational movement and interaction scenarios.

4. Virtual Environment Integration and System Parameters.

After completing the 3D models in Blender, all assets imported into [3] Unity where the virtual training environment was created. All assets were imported using .fbx format to keep all information about geometry and textures applied to them.

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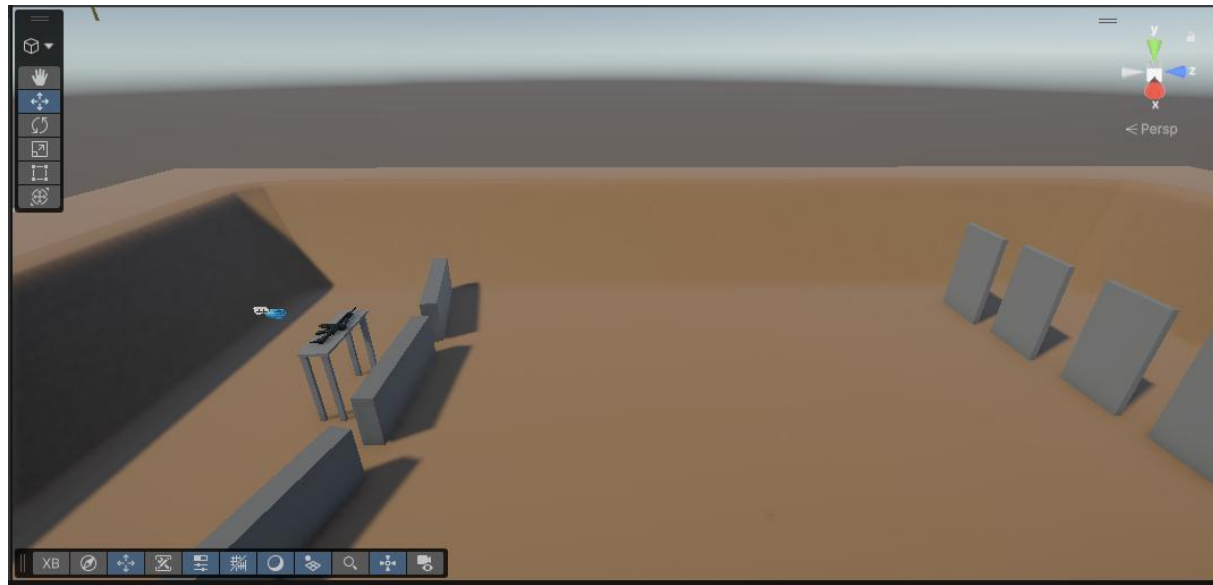


Fig. 3 Scene view in Unity

At this stage, several functional parameters were defined in order to simulate realistic human interaction within the [1] virtual space. These parameters include [5] hand movement tracking, [6] spatial movement of the user inside the playable area, [7] object manipulation mechanics, and positioning of virtual object required for creating a tactical training scenario.

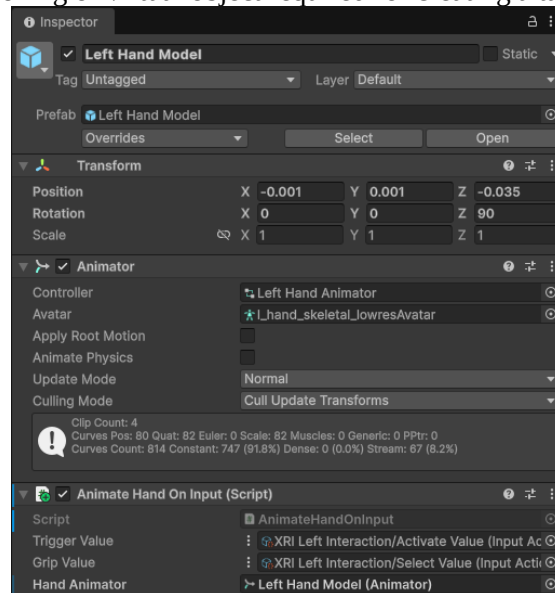


Fig. 4 Hand movement parameters configuration in Unity

A control system attached to the user's left hand was implemented to simulate interaction with the command module, which is situated on the left forearm [9]. Through this interface, the user can activate or deactivate specific features during the simulation.

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Fig. 5 Control System mounted on the forearm

Additionally, [8] a mini-map system was implemented using the visual feed of a second camera mounted on the aerial drone positioned high above the training ground. This feature allows improved situational awareness by offering an overhead perspective of the operational area. At this stage, the drone is considered to be controlled by a different person so the soldier can focus only on the visual feed that is provided into his headset.

5. System Scripting and Functional Implementation

The scripting was developed for implementing the functional logic of the virtual prototype using C# scripts in Unity. These scripts were created to define the weapon firing mechanics, ammunition tracking, object interaction and hand-based controls.

```
1  using UnityEngine;
2  using UnityEngine.InputSystem;
3
4  public class AnimateHandOnInput : MonoBehaviour
5  {
6      public InputActionProperty triggerValue;
7      public InputActionProperty gripValue;
8
9      public Animator handAnimator;
10
11     // Start is called once before the first execution of Update after the MonoBehaviour is created
12     void Start()
13     {
14     }
15
16     // Update is called once per frame
17     void Update()
18     {
19         float trigger = triggerValue.action.ReadValue<float>();
20         float grip = gripValue.action.ReadValue<float>();
21
22         handAnimator.SetFloat("Trigger", trigger);
23         handAnimator.SetFloat("Grip", grip);
24     }
25 }
26
27
28
```

Fig. 6 The Script for hand input

The weapon system decreases ammunition values after each shot and allows to reset the count through a dedicated button mounted on the lower rail of the gun.

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```
1  using UnityEngine;
2
3  public class Pistol : MonoBehaviour
4  {
5      [Header("Bullet Settings")]
6      public GameObject bulletPrefab;
7      public Transform firePoint;
8      public float bulletSpeed = 100f;
9      public float bulletLifetime = 5f; // seconds before bullet is destroyed
10
11      [Header("Audio")]
12      public AudioClip clip;
13      private AudioSource source;
14
15      private void Start()
16      {
17          source = GetComponent();
18
19          if (source == null)
20          {
21              source = gameObject.AddComponent();
22          }
23      }
24
25      public void FireBullet()
26      {
27          // Spawn bullet
28          GameObject bullet = Instantiate(
29              bulletPrefab,
30              firePoint.position,
31              firePoint.rotation
32          );
33
34          // Apply velocity
35          Rigidbody rb = bullet.GetComponent();
36          if (rb != null)
37          {
38              rb.linearVelocity = firePoint.forward * bulletSpeed;
39          }
40
41          // Play gun sound
42          if (clip != null && source != null)
43          {
44              source.PlayOneShot(clip);
45          }
46
47          // Destroy bullet after time
48          Destroy(bullet, bulletLifetime);
49      }
50  }
```

Fig. 7 The gun script

6. System Functionality Testing

The developed prototype allows testing multiple functionalities within the virtual environment. The weapon simulates firing actions and ammunition consumption during the user's testing. The drone provides continuous visual information to the headset as it's flown around the area. As he is navigating through the virtual training area, the user can interact with all the systems simultaneously. This allows the evaluation of how the multiple features operate within a single augment reality platform.



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Fig. 7 POV of the user when starting the simulation

7. Results and Discussion

The prototype successfully integrates multiple systems into a unified virtual platform. The simulation validates the interaction between the weapon model, drone support system, mini-map interface and hand-based controls. These features demonstrate that virtual prototyping can significantly reduce development costs while allowing early identification of design limitations. One major limitation is represented by the absence of physical augmented reality hardware integration. The current version focuses exclusively on software validation. Future improvements may include smart glasses implementation, sensor integration and physical prototype.

8. Conclusions

This paper presented the development of a virtual prototype for an augmented reality military assistance system.

The original contribution added to this project consist of creating most of the 3D assets used in the simulation, developing the virtual training environment, and integrating multiple functional systems such as hand-controlled interactions, ammunition visualization and drone-based mini-map into a new perspective in which the soldier becomes an active component of a mechatronic system that combines human actions with real-time digital assistance.

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INTELLIGENT BALANCE PLATFORM: AN INERTIAL APPROACH TO THE EVALUATION AND TRAINING OF BALANCE

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ABSTRACT:

This research focuses on the development of a smart platform prototype for evaluating postural control, integrating the Nordic Thingy:53 inertial sensor and the Edge Impulse ecosystem. The study demonstrates the technical feasibility of biomechanical data acquisition (at a frequency of 20 Hz) on an unstable inverted BOSU surface. The major theoretical contribution lies in the mathematical conceptualization of novel monitoring metrics: the Spatial Stability Index (ISS), the Recovery Effort Index (IER), and the Kinetic Efficiency Score (SEK). Furthermore, the paper proposes a standardized clinical testing protocol. The developed digital tool establishes the necessary technological foundation for future validation in patients with cerebral dysfunctions.

KEYWORDS: *Cerebral dysfunctions, Inertial sensors, Postural control, Edge Impulse*

1. Introduction

Objective monitoring as the foundation of evidence-based medicine

In the context of neurological rehabilitation, the success of a kinetic program is often evaluated by the patient's functional progress. However, in traditional practice, this relies on visual observations or qualitative scales (such as the Tinetti test or the Berg Balance Scale) which, although useful, suffer from a lack of granularity. In an era of advanced medical technology, the need to quantify the Efficiency of the Kinetic Program through precise biomechanical data has become a priority [1]. The BOSU platform, used in an inverted position (with the rigid base facing up), represents one of the most challenging environments for the postural control system. This configuration induces multidirectional instability, forcing the rapid integration of the visual, vestibular, and somatosensory systems. For the physical therapist, the main challenge lies in demonstrating that, over the course of 10 or 20 physical therapy sessions, the patient's stability parameters improve along a detectable learning curve [2].

The evolution of research and the transition towards clinical validation

This paper represents Part III of the research initiated through hardware exploration and sensor optimization.

- *Paper 1* ("Balance Assessment Technologies: Integration of a Triaxial System") demonstrated the technical feasibility of monitoring an unstable platform, laying the foundation for collecting force and inclination data.
 - *Paper 2* ("System Optimization through IMU Integration") refined this data collection, utilizing inertial units (Nordic Thingy:53) to achieve superior precision in capturing angular velocities and accelerations, eliminating the limitations of purely resistive or capacitive systems.
- In this third stage, the primary objective is to analyze the data and extract relevant conclusions demonstrating the efficiency of the therapeutic program, specifically how a patient's 'stability footprint' changes under the influence of therapeutic exercise.

Objective: Quantifying patient progress and validating the kinetic program

The central objective of this paper is the development and validation of a methodology for assessing clinical progress, utilizing an inverted BOSU platform and the Nordic Thingy:53 sensor.

This objective is broken down into two areas of personal contribution:

1. **The Real-Time Biofeedback System:** Utilizing IMU data to provide the patient with a visual

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reference of the center of gravity, accelerating the motor learning process [5].

2. The Kinetic Efficiency Score (SEK): The algorithm will generate a final report confirming whether the applied exercise program produced a statistically significant improvement in postural control, providing the physical therapist with objective evidence of the intervention's success [6].

Integration of the Thingy:53 Sensor on the BOSU Platform

The Nordic Thingy:53 sensor was mechanically secured to the center of the rigid base of the BOSU device. This positioning was chosen to ensure the correlation of the accelerometer axes with the platform's inclination axes.

Monitoring Architecture: nRF Edge Impulse and Edge Impulse Studio

In the current phase of the research, a cloud-native data acquisition workflow has been implemented, utilizing the synergy between the nRF Edge Impulse mobile application and the Edge Impulse Studio analytics platform. This configuration enables the transformation of the BOSU device from a purely mechanical piece of equipment into an intelligent assessment system, while maintaining scientific rigor.

Rolul aplicației mobile nRF Edge Impulse (Gateway)

The nRF Edge Impulse application installed on the mobile device served as the communication interface and gateway between the Thingy:53 sensor and the virtual storage environment.

Configuration was performed based on the optimal parameters for balance biomechanics:

- **BLE Connectivity:** The sensor was identified via its unique hardware address, ensuring a stable connection between the BOSU platform and the mobile device.
- **Sensor Configuration:** The 'Inertial' operating mode was selected, enabling sensor fusion between the accelerometer and gyroscope to eliminate the noise errors identified in previous testing.
- **Data Sampling:** A sampling frequency of **20 Hz** and a **sample duration of 30 seconds** were established—values documented in literature as sufficient for capturing postural oscillations without overloading data transmission.

Simultaneously, a laptop was used to access the Edge Impulse Studio platform. This interface enabled enhanced data management, contributing to the originality of the proposed solution:

- **Session Control (Data Acquisition):** The sampling process was initiated from the laptop, with the mobile application serving solely as a transmitter. This allowed the physical therapist to closely monitor the patient's posture while simultaneously tracking signal quality on an extended display.
- **Signal Visualization:** The preview window on the laptop was utilized to analyze waveforms in real time, allowing for the rapid identification of the subject's major biomechanical deviations on the inverted BOSU.

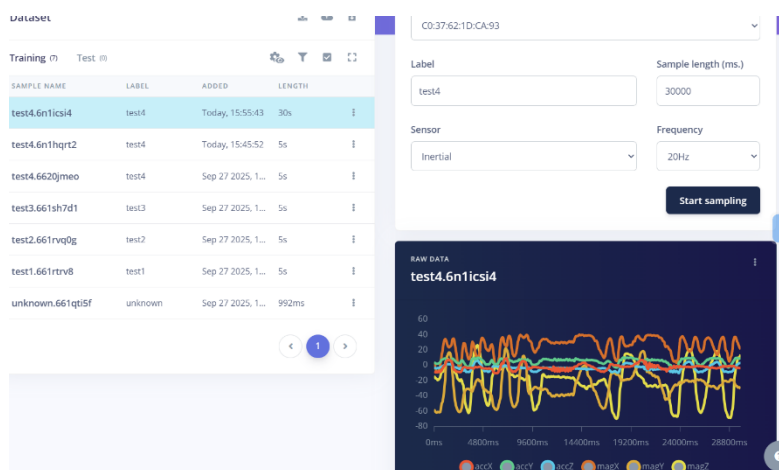


Figure 1: Edge Impulse application settings on the laptop (Personal archive)

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Defining the Concept of the Kinetic Efficiency Score (SEK)

The Kinetic Efficiency Score (SEK) is defined in this paper as a composite numerical indicator designed to objectively quantify a subject's postural stability on the inverted BOSU platform. Unlike traditional clinical scales (such as the Berg Balance Scale or the Tinetti Test), which provide a discrete assessment dependent on the examiner's subjective observation [1], KES represents a continuous measure derived directly from the dynamics of forces and rotational moments captured by the inertial measurement unit (IMU) [2].

This score does not merely measure the presence or absence of imbalance at a specific moment, but analyzes the overall quality of motor control: how rapidly postural deviations are detected and how effective the applied neuromuscular micro-corrections are in maintaining the center of gravity within the base of support [3].

The definition of SEK is based on the digital signal processing of samples collected over a standard 30-second window (at a sampling frequency of 20 Hz). The algorithm utilizes the data provided by the accelerometer and gyroscope of the Nordic Thingy:53 sensor to calculate two primary biomechanical vectors, which are well-grounded in the specialized literature of stabilometry:

1. Spatial Stability Index (ISS)

The SSI is derived from the angular deviation of the platform along the sagittal (Pitch, θ) and frontal (Roll, ϕ). To obtain an average of the deviation from the ideal horizontal plane, the root mean square value is utilized:

$$ISS = \sqrt{\frac{1}{N} \sum_{i=1}^N (\theta_i^2 + \phi_i^2)} \quad (1)$$

where N represents the total number of samples. From a clinical perspective, a high ISS value indicates a wide 'stability footprint', suggesting a major deficit in postural alignment [5].

2. Recovery Effort Index (IER):

While the ISS measures the amplitude of motion, the IER measures its dynamics, being extracted directly from the gyroscope data. The IER reflects the angular velocity at which the patient performs compensatory corrections.

$$IER = \sqrt{\frac{1}{N} \sum_{i=1}^N (\omega_{x,i}^2 + \omega_{y,i}^2)} \quad (2)$$

where $\omega_{x,i}$ and $\omega_{y,i}$ represent the angular velocities along the sagittal and frontal axes at sample i. High angular velocities (an increased IER) indicate jerky movements, characteristic of a proprioceptive system that reacts late to balance perturbations, resorting to a 'hip strategy' or trunk movements, thereby consuming a disproportionate amount of neuromuscular energy [7].

The SEK Equation:

The final score is calculated by normalizing these indices on a scale from 0 to 100, where the maximum value represents theoretically perfect balance:

$$SEK = 100x \left(1 - \frac{ISS_{patient} + k \cdot IER_{patient}}{Max_{theoretical}} \right) \quad (3)$$

where k represents a weighting coefficient that adjusts the importance of the reaction speed relative to the oscillation amplitude, a mathematical model adapted from the kinematic assessment algorithms proposed in the neuromotor rehabilitation literature [8].

Defining the value ranges for each indicator and correlating them with postural strategies established

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in the literature

ISS quantifies the magnitude of the angular deviation (in degrees) of the center of mass. The maximum physical value the BOSU platform can record before its rigid edge touches the ground is approximately 25° - 30°, a point considered the 'fall limit' [9].

Clinical Interpretation of SSI Values

Table 1. Clinical Interpretation of SSI Values

ISS Interval	Rating	Significance
1° - 5°	Optimal	The sway area is minimal. The proprioceptive system maintains the center of gravity strictly above the base of support. Indicates excellent postural control and complete sensorimotor integration [10].
6° - 15°	Compensated	Visible oscillations; the patient explores the limits of stability. Balance is maintained but requires continuous corrections. Characteristic of the intermediate phases of neuroplasticity [11].
> 15°	Deficient	Large angular deviations that bring the platform close to its mechanical tipping limit. Indicates a lack of motor control, insufficient stabilizing strength at the ankle level, or severe proprioceptive latency [9].

The **IER** quantifies the angular velocity (degrees per second, °/s) of compensatory movements. According to studies based on inertial sensor fusion [8], the velocity of the corrections dictates the type of motor strategy adopted by the central nervous system.

Clinical Interpretation of IER Values

Table 2. Clinical Interpretation of IER Values

IER Interval	Strategy	Significance
5°/s - 20°/s	Ankle Strategy	Fine, slow, and automatic postural corrections mediated by myotatic (stretch) reflexes. Indicates minimal energy consumption and optimal functioning of the muscle spindles [5].
21°/s - 50°/s	Conscious Effort	Visible oscillations; the patient explores the limits of stability. Balance is maintained but requires continuous corrections. Characteristic of the intermediate phases of neuroplasticity [11].
> 50°/s	Hip Strategy	Large angular deviations that bring the platform close to its mechanical tipping limit. Indicates a lack of motor control, insufficient stabilizing strength at the ankle level, or severe proprioceptive latency [12].

The SEK integrates amplitude (ISS) and dynamics (IER) into a single percentage value (0 - 100), providing a comprehensive overview of performance. The interpretation model was structured in accordance with the scaling principles used in rehabilitation biofeedback [3].

Clinical Interpretation of SEK Values

Table 3. Clinical Interpretation of SEK Values

SEK Interval	Recovery Stage	Physical Therapy Recommendation
76 - 100	Functional Balance	Therapeutic objective achieved. Corrections are automatic (low IER) and the deviation amplitude is minimal (low ISS). Progression to plyometric exercises or sports reintegration is recommended

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41 - 75	Developing Control	The patient exhibits instability but possesses the capacity to right themselves (moderate/high ISS, but moderate IER). The program requires continued stimulation on unstable surfaces, alongside a gradual increase in cognitive difficulty (e.g., dual-task training) [14].
0 - 40	High Fall Risk	Characterized by a combination of extreme tilt (high ISS) and stiffness/jerky movements (high IER). The inverted BOSU exercise is too advanced. Regression to exercises on a stable plane or the dome side of the BOSU (dome side up) is recommended, under strict physical assistance [2].

Standardized Testing Protocol

To validate the accuracy of the Nordic Thingy:53 sensor and the clinical utility of the Kinetic Efficiency Score (SEK), a standardized testing protocol was designed and implemented. This protocol comprises five specific tests executed on the inverted BOSU platform, designed to evaluate different components of postural control: proprioception, directional precision, endurance, movement dynamics, and reaction time.

To provide a quick visual reference of how biomechanical parameters respond within each clinical test, the evaluation matrix below was developed. This matrix facilitates the interpretation of data extracted from the Edge Impulse platform by specialized medical personnel.

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Table 4. Clinical Assessment via the Edge Impulse Ecosystem			
Clinical Test Name	Clinical Parameter	Reference Range	Clinical Interpretation (Normal vs. Pathological)
1. Modified Romberg	Sensorimotor integration and visual dependency.	ISS: < 10° (eyes closed) IER: < 30°/s SEK: Maintained > 70	Normal: Minor increase in sway area upon removal of visual input; proprioception compensates effectively. Pathological: Massive increase in ISS (> 15°) and a collapse of the SEK. Indicates a major proprioceptive or vestibular deficit (high visual dependency).
2. The "Clock" (Weight Transfer)	Voluntary directional control	ISS: 10° - 15° (intentional tilt) IER: < 20°/s (smooth movement) SEK: N/A (amplitude test)	Normal: The patient achieves the required amplitude (visible ISS) with a low recovery velocity, maintaining smooth motor control. Pathological: Very high IER (> 50°/s). Movement is jerky and rigid; the patient resorts to sudden jerks to avoid losing balance.
3. Single-Leg Stance (Duration: 30 seconds)	Local muscular endurance and fatigue detection	ISS: < 8° (in the first 20s) IER: No sudden "spikes" SEK: > 65 throughout	Normal: Stable, constant values maintained through the fine ankle strategy. Pathological (Fatigue): Values are initially optimal, but during the final 10 seconds, the REI suddenly spikes, indicating muscle spindle exhaustion and the triggering of gross compensations.
4. Dynamic Squat	Strength symmetry within a closed kinetic chain.	ISS: 0° - 3° (no lateral deviation) IER: Constant, < 25°/s SEK: > 80	Normal: The center of gravity descends perfectly along the vertical axis; the frontal axis ISS (left-right / Roll) remains close to 0°. Pathological: An increase in Roll ISS indicates compensation via the dominant lower limb (due to strength asymmetry or fear of loading the affected limb).
5. Reaction to Perturbations (External Impulse)	Recovery time of postural reflexes	IER: Permissible (> 60°/s) at impact Stabilization time: < 3 seconds to return to SEK > 75	Normal: The nervous system promptly detects the impulse and restores the platform to a stable state in under 3 seconds. Pathological: Prolonged stabilization time (> 5 seconds) or an absolute inability to right oneself (fall). Indicates an elevated risk of falls in daily life.

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In conclusion, the system architecture proposed in this work provides a solid technological foundation, equipping the field of rehabilitation engineering with an instrument ready for extensive clinical testing and validation within evidence-based medicine protocols.

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Recovery SPA Center for people with mobility issues

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This study examines the current level of aquatic accessibility in Romania for individuals with mobility issues and proposes an integrated SPA center concept located near the seaside. The research combines theoretical analysis of physical and informational barriers, evaluation of national balneological resources, review of assistive access technologies, and a questionnaire applied to 20 participants with various locomotor limitations. Findings reveal structural and systemic deficiencies in existing facilities, despite the well-documented therapeutic benefits of aquatic environments. The study demonstrates the feasibility of implementing a sustainable, user-centered model that integrates inclusive design, safety systems, and modern transfer technologies. The concept aims to enhance autonomy, rehabilitation efficiency, and quality of life.

KEYWORDS: Assistive Equipment, aquatic accessibility, reduced mobility, rehabilitation, SPA

1. Introduction and theoretical foundation

Access to the aquatic environment represents not only a recreational activity but an essential therapeutic tool for numerous categories of people. This paper substantiates the need for an accessible therapeutic aquatic space, aiming at the rehabilitation and social inclusion of individuals with mobility difficulties, a broad category that includes both wheelchair users and people with temporary or age-related motor limitations. I deliberately opted for the phrase "mobility difficulties" instead of terms like "handicap" or "special needs". In the applied questionnaire, the use of this neutral phrasing favored obtaining more responses, eliminating the initial reluctance observed among the majority of respondents. In the case of neurological, degenerative orthopedic, or post-traumatic conditions, aquatic therapy contributes to reducing pain, relieving stiffness, increasing mobility, improving balance, and regaining independence. Their access to recovery facilities is severely restricted. This research direction is motivated by experience in physiotherapy, the direct confrontation with local infrastructure deficiencies experienced within the family environment, as well as the observation of international good practices (Switzerland, Spain, Türkiye, Greece) regarding universal accessibility.

Building on the international study conducted by Eleni M. and Sarah J. Hilton, which demonstrated that the SPA industry ignores the needs of people with reduced mobility, and expanding the original sample from 9 to 20 participants, the current paper examines the 4 major categories of barriers identified by the authors. Informational barriers consist of the absence of

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precise data on websites regarding the accessibility level of locations and the inadequate communication of the staff, generating anxiety and abandonment right from the travel planning phase. Physical barriers represent the most restrictive obstacle, including unadapted environmental and architectural elements, such as non-compliant ramps, narrow doors, inaccessible furniture, and the absence of adapted restrooms. Social barriers stem from the staff's lack of training and empathy, who often address companions instead of speaking directly to the affected person, with negative attitudes frequently generating humiliating experiences for the beneficiaries. Finally, intrinsic barriers are dictated by individual physical and psychological limitations, where chronic pain, dependence on companions, and the fear of hostile environments discourage participation in recovery programs [1].

These theoretical concepts are confirmed by the reality of the Romanian seaside and urban space, documented through the testimonies of a wheelchair user, Alina P. Her accounts demonstrate that, although a theoretical legislative framework exists, local infrastructure is characterized by ramps built exclusively to avoid fines, featuring non-compliant inclines that force family members to intervene physically, as in the case of her father having to carry her up the stairs. Damaged sidewalks and high curbs force users to travel directly on the road, among cars. In public transport, some bus drivers refuse to lower the ramps, claiming they are in a hurry, while railway staff are forced to improvise to board patients onto trains. The psychological impact is devastating, exacerbated by apathetic passersby who suggest that people with disabilities should stay at home so as not to "get in the way" [2].

In the hotel and medical sectors, except for isolated facilities that comply with space and equipment standards, most buildings feature high thresholds, lack of specialized equipment, and hard-to-access pools. A gradual modernization process can be observed on the seaside, recent evaluations confirm that accessibility in Romania remains partial, inconsistent, and treated as a bureaucratic formality. This analysis of reality demonstrates that the lack of infrastructure is not a technical issue, but a form of systemic exclusion, fully justifying the need to build a modern rehab center. The purpose of the research was to evaluate the current level of accessibility and to develop an applicable concept that integrates validated technological solutions, natural resources, and inclusive design principles.

2. The Sea as an Active Recovery Factor – Romania's Balneotherapy Potential

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Thalassotherapy goes beyond simple relaxation, being an integrated medical program that harnesses the synergy of the marine ecosystem: water, algae, mud, and saline air. Rich in sodium and chlorine, seawater acts directly on cellular pressure, effectively reducing inflammation and pain. Locating a rehabilitation center on the seashore is a vital strategic approach for the efficiency of the treatments. The proposed center does not promise a complete recovery, but rather the improvement of health, independence, and social inclusion. The abundance of balneary resources gives Romania a privileged European position. The effectiveness of mineral waters and muds is scientifically validated, offering unique physical and psychological recovery, especially for post-stroke patients or those with severe arthrosis (pathologies also found among the questionnaire respondents).

Although the aging population generates a valuable and constant tourist demand, the huge potential of the over 500 balneary units is hindered by critical structural deficiencies: a shortage of specialized and empathetic staff, bureaucracy, and, fundamentally, an infrastructure not aligned with international accessibility standards [3].

The analysis of Bihor County illustrates the contrast between the abundance of resources and their utilization. Resorts such as Băile Felix and Băile 1 Mai use thermomineral waters (80°C) with exceptional results in reducing pain, treating over 130,000 elderly people in a decade at Băile 1 Mai alone. However, out of 75 localities with proven thermal potential, only 8 have functional infrastructure. The success of developed resorts demonstrates the necessary direction: integrating natural resources with modern technology in fully accessible centers, transforming this raw potential into a continuous and inclusive therapeutic journey.

3. Technological evolution and access solutions

While the first lifts in the 1980s relied on water pressure and external assistance, innovations gradually introduced independence through battery-powered systems. Although the equipment is technically divided into stationary or mobile models, the major problem in public facilities in Romania remains poor maintenance, which turns these legally mandatory lifts into useless obstacles. To ensure inclusion, modern technology proposes fully autonomous solutions. A great example is the Seatrac system, developed in Greece, which uses a solar-powered modular track to allow wheelchair users to enter the sea without any external help. In the controlled environment of swimming pools, various types of lifts and platforms are of great

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help, operating on water pressure, allowing access with a wheelchair.

The transition from land to the aquatic environment is facilitated by the use of MobiMat mats, derived from military technology, which stabilize movement on the sand. In addition, amphibious chairs offer dual mobility, allowing a fluid transition from the beach into the water. For safety and dignity during immersion, adaptive swimwear equipped with magnetic closures is of particular importance. Inside the center, recovery efficiency is maximized through advanced medical equipment, such as underwater bicycles and traction systems that perform spinal elongation directly in the thermal water [4].

Beyond this equipment, the future of rehabilitation belongs to assistive technologies, such as exoskeletons. These support both patients in regaining their balance and medical staff, reducing the physical strain caused by handling heavy weights. Adaptation to the aquatic environment requires dedicated prosthetic solutions, either through vacuum-sealed waterproof covers that protect the prostheses or through water-resistant attachments that compensate for the missing limb. The impact of personalized innovation is illustrated by the case of a Spanish teenager with severe hemiparesis following a stroke. For him, the use of 3D printing allowed the rapid creation of a swimming paddle adapted to his biomechanics, restoring his balance in the water at a low cost. This technical intervention demonstrates that modern technology can quickly restore patients functionality and confidence, directly arguing for the necessity of integrating smart equipment and rapid prototyping in a recovery center anchored in the realities of the 21st century [5].

4. Methodology and questionnaire analysis

The analysis of the 20 real cases (16–83 years old; 10 male, 10 female) demonstrates that the need for accessibility is a daily medical emergency. The participants face severe limitations caused by neurological, orthopedic, and post-traumatic conditions. In cases of tetraplegia, stroke, muscular dystrophy, or Wilson's disease, patients depend on constant assistance, suffering from rigidity and tremors. For them, unloading body weight in water is the only method that alleviates involuntary movements and allows for neuromotor re-education in a safe environment. The situation is equally critical for patients with degenerative orthopedic conditions, such as coxarthrosis, gonarthrosis, or femoral head necrosis. The lack of adapted infrastructure turns even a simple outing into an extreme effort, a fact confirmed by a patient

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with a lower limb amputation, who highlighted that accessing his own apartment building is impossible without help, as the existing ramps are unusable. All these testimonies validate the need for an aquatic recovery center; the conclusion of all these cases is that, although the needs are complex, water provides the perfect setting for integrated rehabilitation, the essential condition being the guarantee of facilitated access.

To identify the optimal location for such a center, the Romanian coastline was evaluated using an accessibility scoring system from 0 to 8, inspired by a Spanish study [6][7]. Areas such as Tuzla rank at the lower levels due to minimal infrastructure and sedimentary dynamics, making them suitable only for removable walkways. Places like Costinești offer a medium level of accessibility, requiring an expansion of facilities. The higher levels, rated 6-8, are found in intensely modernized tourist areas, such as Mamaia and Mangalia, that already have floating chairs and ramps, representing the ideal environment for implementing autonomous access systems and developing a rehabilitation center.

In addition to urban infrastructure, the research proposes an innovative and sustainable technical solution based on the circular economy: creating an adapted lounge chair and an access walkway through the structural reuse of decommissioned wind turbine blades. The fiberglass provides extreme durability in the corrosive marine environment, while the natural curvature of the blade mimics the physiological curves of the spine, offering superior ergonomic support and reducing pressure points for users with reduced mobility. The lounge chair is designed to support a patient weight of up to 130 kg. The automated hydraulic mechanism, which would allow lifting and tilting for an independent transfer, was sized for a total mass of 290 kg, requiring a calculated lifting force of over 3500 N, thus ensuring a completely safe and reliable operation. It generated major interest in the questionnaire, with 16 respondents expressing the desire to use it.

5. Proposed concept

The design of the rehabilitation center proposes a unitary architectural concept, where technical rigor harmoniously blends with empathy and respect for the user. Grounded in theoretical research and the actual needs of the respondents, the vision defines accessibility as an uninterrupted spatial flow, free from stress and additional effort. The functionality of the complex depends on perfect continuity, where a single obstacle can nullify the utility of the

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entire system. Consequently, the architecture adapts to the individual, guaranteeing safe and autonomous movement. This fluid experience begins in the online environment, an aspect considered extremely useful by the study participants. A dedicated web platform would provide a virtual tour, interactive maps, and a detailed descriptive PDF guide, essential tools that would eliminate the anxiety of the unknown and allow prior familiarization with the facilities, thus paving the way for a barrier-free visit.

The transition to the physical environment is achieved through generously sized parking lots and routes that naturally lead to automated entrances. Inside, the corridors, locker rooms, and restrooms are ergonomically redesigned to restore dignity and personal control, featuring wide maneuvering spaces, accessible lockers, and threshold-free toilets. Safety is an absolute priority, yet subtly integrated to avoid a cold atmosphere. Non-slip flooring, rapid drainage systems, motion sensors, and panic buttons would offer invisible but effective protection, supported by a strict intervention protocol.

The heart of the center is the hydrotherapy area, featuring optimized pools (1.30 m depth) where soft lighting, chromotherapy, and controlled acoustics induce a state of profound relaxation. The pools become spaces of gravitational release, accessible via gentle ramps and pool lifts compliant with international standards. The water temperature is rigorously calibrated, ranging 28 - 32°C, to support neuromotor rehabilitation and muscle relaxation.

The success of recovery depends on the infrastructure, but equally on human will, an aspect also demonstrated by Paralympic athletes. G. Patterson, an Australian swimmer born with diastrophic dysplasia, achieved sporting excellence on a global scale. S. Galleguillo, an Argentine swimmer, refused to let the pandemic stop his training, building his own improvised pool in his backyard to maintain his mobility and coordination. These examples confirm that water is a medium of liberation. The purpose of the proposed center is to provide that safe space where disability becomes merely a starting point, not a final destination.

6. Conclusions

By identifying, translating, and synthesizing international literature, and analyzing barriers correlated with direct field observations, the research confirms the nascent stage of aquatic accessibility in Romania. Although respondents associate hydrotherapy with pain

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reduction and psychological safety, the deficient infrastructure blocks these theoretical benefits. For effective recovery, users require a continuous therapeutic path, predictable access, and intuitive equipment to restore their autonomy.

Methodologically, the research expanded the reference study (M&H) to a sample of 20 individuals, grouped into 3 clinical categories, using a questionnaire focused on the 4 validated barriers. The responses substantiate a major conclusion: patient dependency is primarily driven by the hostility of the built environment rather than the severity of the medical diagnosis. Although they unanimously acknowledge the analgesic effects of water, patients abandon recovery due to physical barriers (absence of ramps and safe transfer systems) and informational barriers (16 participants complained about the lack of online transparency regarding facilities). This architectural and communicational inadequacy maintains uncertainty, culminating in a fear of accidents, frustration, and social isolation.

The documentation was supported by international observations of best practices in the accessibility sector and rigorous photographic field documentation (Mangalia, Bucharest). The physical realities and environmental obstacles were confirmed both through personal experience assisting a tetraplegic patient and, to ensure impartiality, through the accounts on Alina Petruța's blog regarding the challenges faced by wheelchair users. Based on these data and coastal dynamics factors, a custom ranking table for the accessibility of Romanian beaches was created, adapted from a Spanish evaluation model.

On an applied level, the project proposes a recovery center located on the Black Sea coast, spatially designed as a continuous flow to maximize autonomy. This location capitalizes on the current modernization of the coastline to combine thalassotherapy with Romania's balneoclimateric potential, which ranks highly in Europe but remains insufficiently utilized. As an element of sustainability and innovation, a system consisting of an ergonomic sunbed made from recycled wind turbine blades was proposed. The specific curvature of the blade mirrors the physiological curvatures of the spine, reducing pressure points.

The research validates the need to transition from isolated and often dysfunctional architectural interventions to an integrated and predictable system, designed to ensure functionality, independence, and the absolute safety of users. To combat public reluctance, modern technological solutions were rigorously documented, including pool hoists, amphibious chairs (Mobi-chair), autonomous systems (Seatrac), 3D printing devices, and

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spinal traction equipment, etc. These examples confirm that the necessary tools exist, and their integration drastically reduces mobility barriers and accelerates the recovery process.

To eliminate informational barriers, a transparent digital ecosystem was proposed: easy localization on Google Maps, a downloadable PDF guide, and an online virtual tour. These tools allow the beneficiary to familiarize themselves with the space beforehand, reducing the anxiety of the unknown and boosting morale toward healing. Finally, the visual component includes sketches initially drawn on paper and digitally processed, culminating in the generation of a final image of the architectural concept, obtained after multiple iterations and processing in the specialized software mentioned in the references.



Fig. 1. Example of an online platform providing information regarding the center's accessibility



Fig. 2. Main pool equipped with a properly inclined ramp and a Reval-type access platform¹

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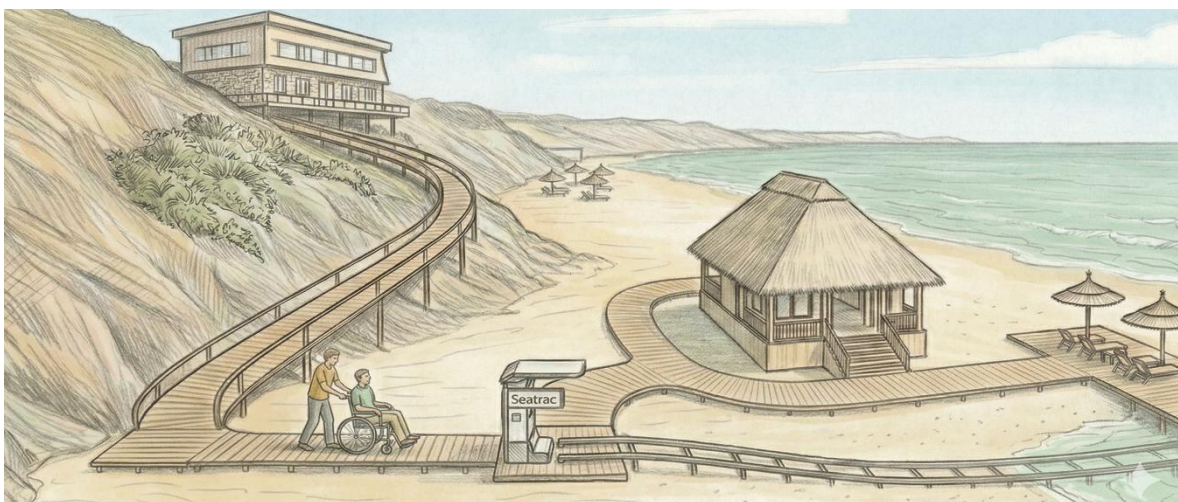


Fig. 3. Proposed concept located on the coast, with Seatrac area, walkway, adapted locker & WC

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Polly : Multifunctional Educational Robot

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Abstract

POLLY is a multifunctional educational robot developed on the Arduino Uno platform for STEM learning and robotics applications. The robot integrates electronics, mechanics, and software into a compact modular system capable of operating in five modes: line following, obstacle avoidance, object following, infrared remote control, and stop mode. Polly uses accessible hardware components such as DC motors, IR sensors, an ultrasonic sensor, a servo motor, and an L298N motor driver. The software was created in the Arduino IDE using a modular programming structure that simplifies maintenance and future upgrades. Testing confirmed reliable autonomous and remote-controlled operation in different scenarios. The project demonstrates how low-cost robotic platforms can support practical education, technological experimentation, and the development of problem-solving skills in robotics and automation.

1. Introduction

Polly is an educational robot developed on the Arduino Uno platform, designed to promote hands-on learning, technological exploration, and participation in robotics competitions. The project emphasizes innovation, adaptability, and practical implementation, making it a highly suitable tool for academic environments and extracurricular technical activities. This robot seamlessly integrates electronics, mechanics, and software engineering into a compact, modular system capable of performing multiple complex tasks.

Polly features five distinct operating modes, each demonstrating different robotic behaviors and functions. These modes are integrated seamlessly into a single platform and can be selected and controlled using an infrared (IR) remote, allowing users to interact with and explore its capabilities in real time. Polly serves a dual role: as an educational platform for introducing students to core STEM concepts, and as a proof of concept illustrating how low-cost hardware such as Arduino can be leveraged to develop intelligent and versatile robotic systems. Through this project, learners engage in problem-solving, systems thinking, and iterative design—skills that are increasingly relevant in robotics and automation.

2. Current State of the Field

2.1. De Facto Standards in Educational Robotics

Microcontroller platforms like Arduino are widely used in educational and hobbyist robotics due to affordability, ease of use, and strong community support. For small-scale autonomous robots like Polly, common components include IR remote control systems, basic motor drivers, and line-following sensors. These tools provide a practical foundation for exploring robotics without requiring advanced programming or hardware experience.

2.2. Industry or Widely Adopted Standards

In contrast to hobbyist approaches, industry standards in robotics typically involve more advanced systems such as Raspberry Pi for high-level processing, or the use of the Robot Operating System (ROS) for software integration. Professional robots also rely on advanced sensors (e.g., LiDAR, stereo cameras), wireless communication (e.g., Bluetooth, Wi-Fi, or Zigbee), and steering systems that enable more realistic navigation control, such as servo-based or Ackermann steering. While Polly uses more basic technologies, it aligns with widely adopted educational practices that focus on accessibility and modularity.

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2.3. Proposed Improvements

In Polly's case, several potential improvements were identified during development. One key enhancement would be the integration of Bluetooth control, to expand remote interaction options beyond infrared. Additionally, upgrading the robot's steering system—potentially through a servo-based front-wheel steering mechanism—would enable more precise and realistic navigation, moving beyond simple differential turning. The line-following functionality could also benefit from more accurate and reliable sensors, which would improve tracking performance on complex paths. Overall, these improvements aim to bring Polly closer to real-world robotics applications, while maintaining its educational value.

3. Hardware Resources and Implementation

Polly's hardware combines a compact mechanical structure with essential electronic components for autonomous and remote-controlled operation. Designed for modularity and educational clarity, it uses widely available Arduino-compatible components for easy assembly, troubleshooting, and future upgrades.

3.1. Mechanical Structure

Polly's chassis is lightweight, optimized for stability and maneuverability, and supports four independent DC gear motors. This four-wheel drive configuration ensures better traction and precise differential control. Power is supplied by two Samsung 18650 Li-Ion batteries (3.7V, 2600mAh), connected through a TP4056 charging module that provides protection against overcharge, short-circuit, and reverse polarity. The chassis is durable and adaptable for classroom, demo, and competition use.

3.2. Electronic Components and Motor Control

The core of the robot is an Arduino Uno R3 microcontroller, responsible for managing sensor input, decision logic, and motor control. The driving system consists of an L298N Dual H-Bridge Motor Driver, which controls the speed and direction of all four motors. The motors on the right side are connected to pins 5 (enable), 7, and 8, while the left motors connect to pins 6 (enable), 9, and 10. The motor driver enables both speed modulation using PWM signals (via enable pins) and direction control by setting the appropriate logic levels on input pins.

3.3. Sensors Integration

- 4× Infrared (IR) Sensor Modules: Two are used for line-following (connected to analog pins A0 and A1), and two for object-tracking functionalities (connected to pins A2 and A3).
- 1× Ultrasonic Sensor (HC-SR04): Enables obstacle detection by measuring the distance to surrounding objects (connected via pins 11 for trigger and 12 for echo).
- 1× Micro Servo Motor (SG90): Mounted with the ultrasonic sensor on pin 4, it allows for directional scanning by rotating the sensor left and right.
- 1× IR Receiver Module: Enables wireless control via an infrared remote connected to digital pin 3, allowing the user to switch between the five operating modes.

3.4. Electrical Connections and Pin Mapping

All components share a common ground reference to prevent voltage discrepancies. The battery output is distributed to the Arduino, sensors, and motor driver, with regulated voltage where necessary.

Component	Arduino Pin(s)
Right Motors	5, 7, 8

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Component	Arduino Pin(s)
Left Motors	6, 9, 10
IR Receiver	3
Ultrasonic Sensor	11 (Trig), 12 (Echo)
Servo Motor	4
IR Line Sensors	A0, A1
IR Object Sensors	A2, A3

Table 1: Hardware Pin Mapping

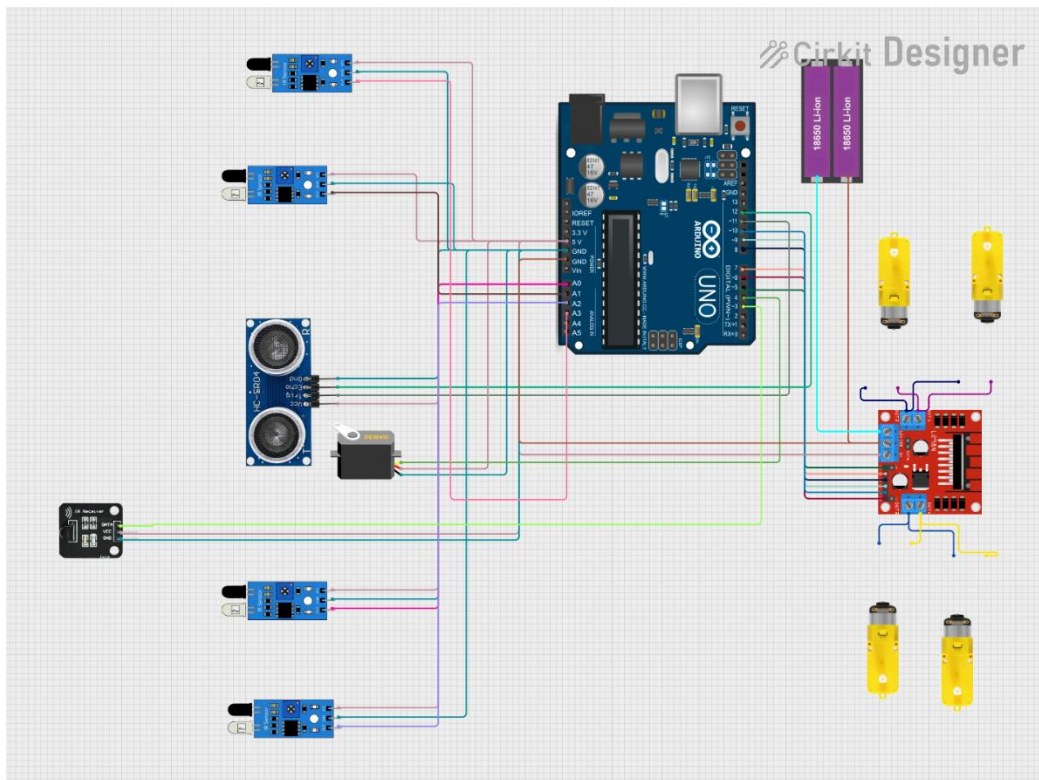


Fig. 1. Electrical Diagram Model

4. Software Resources and Implementation

The software development for Polly was carried out using the Arduino IDE, a widely adopted open-source platform that supports C/C++ programming tailored for Arduino-compatible microcontrollers. The codebase is structured in a modular format, allowing for clear separation of functionalities and easier debugging, expansion, or customization.

4.1. Programming Environment and Tools

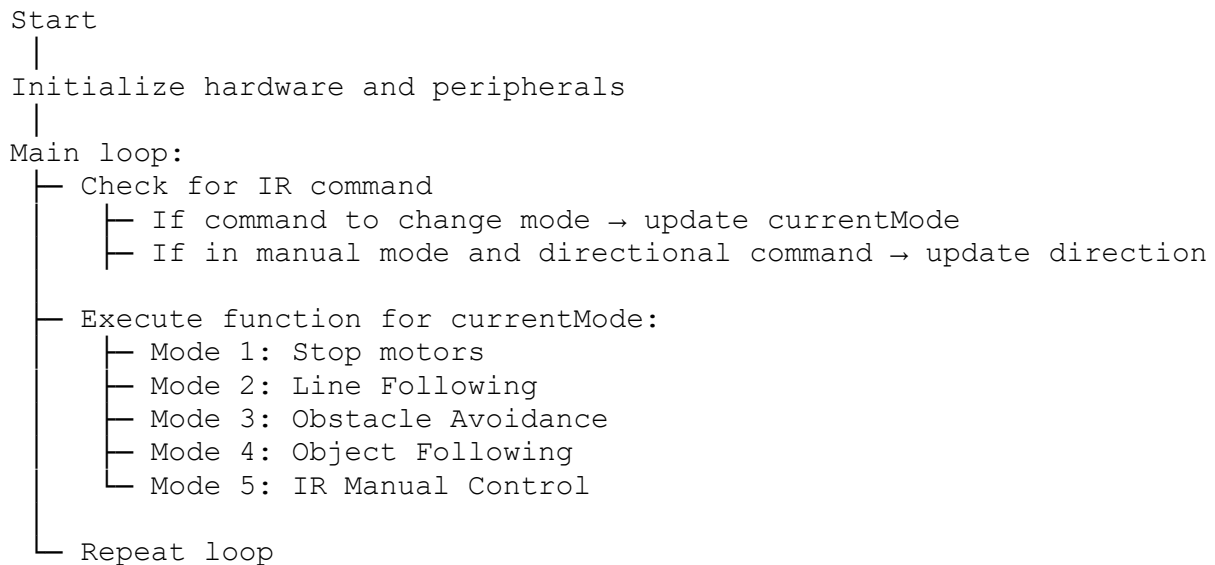
- Arduino IDE: Used for writing, compiling, and uploading code to the Arduino Uno board.

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- IRremote Library: Facilitates decoding of infrared signals from the remote control.
- Servo Library: Enables precise control of the SG90 servo motor for ultrasonic scanning.
- NewPing Library: Optimizes distance measurements using the HC-SR04 ultrasonic sensor, offering improved performance over the default pulseIn function.

4.2. Code Structure, Logic, and Flow

The robot's logic is divided into five main functional blocks, each corresponding to one of the operating modes. A central control loop continuously monitors the IR receiver to detect remote control inputs and switches the active mode based on predefined IR codes. Motor control is abstracted into a reusable function named `rotateMotor()`, which receives parameters for direction and speed, simplifying motion handling across different modes.



4.3. Operating Modes Execution

1. Mode 1 (Stop): Cease all motor activity and remain stationary.
2. Mode 2 (Line Following): Execute a line-following routine using analog readings from two IR sensors (A0, A1) to maintain the track.
3. Mode 3 (Obstacle Avoidance): Perform obstacle avoidance by analyzing distance values and scanning for alternative paths using the servo-mounted ultrasonic sensor.
4. Mode 4 (Object Following): Carry out object following by comparing input from two additional IR sensors (A2, A3).
5. Mode 5 (IR Control): Respond to manual IR commands for directional control (forward, backward, left, right, stop).

5. Testing and Demonstration

5.1. Obstacle Avoidance Test

Polly was placed on a flat surface with randomly positioned obstacles. The ultrasonic sensor detected objects within a 10–30 cm range. The servo motor efficiently rotated the sensor left and right to find the clearest path. During testing, the robot adjusted its trajectory in real-time, successfully avoiding obstacles in all test runs.

5.2. Demonstration Plan and Mode Transitions

Polly demonstrates its functionality sequentially across the following structured mode transition: Idle → Manual → Line Following → Obstacle Avoidance → Demo → Idle

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This structure ensures smooth demonstration of all capabilities, emphasizing educational and operational clarity.

6. Conclusions and Future Work

The Polly educational robot successfully demonstrates the integration of multiple functionalities within a compact and accessible Arduino-based platform. Through the development and implementation of five distinct operational modes, Polly exemplifies versatility in robotics design, making it an effective tool for STEM education and competitive participation.

6.1. General Observations

- **Multifunctionality:** Combining diverse capabilities into a single platform allowed for efficient use of hardware components.
- **Modularity:** The clear separation of hardware and software modules facilitated troubleshooting, maintenance, and incremental upgrades.
- **Educational Value:** Polly's design encourages hands-on learning in electronics, programming, and mechanical assembly.

6.2. Implementation Challenges

- **Sensor Limitations:** Basic IR sensors and ultrasonic modules occasionally introduced noise and detection inaccuracies in varying lighting or reflective environments.
- **Control Method:** The IR remote control presented range and interference constraints that limited mobility.
- **Mechanical Steering:** The differential drive mechanism lacked the precision of a dedicated steering system, causing difficulty in sharp turns.

6.3. Future Improvements

- **Wireless Control Upgrade:** Implementing Bluetooth or Wi-Fi control for flexible command input via mobile devices.
- **Enhanced Sensors:** Supplementing existing sensors with higher-precision alternatives (e.g., LIDAR or array sensors).
- **Steering Mechanism:** Introducing a servo-driven steering assembly for coordinated wheel turning.
- **Algorithm Optimization:** Refining control algorithms for adaptive speed regulation and sensor data filtering.”.