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Improvement proposal to automate the process of sorting materials in the recycling sector using the Internet of Things (IoT)

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Abstract– ***Advances in manufacturing have driven the development of automated systems that improve efficiency in industrial processes such as recycling. In this context, the implementation of automation and sensor technologies in recycling plants is essential for the accurate classification of recyclable materials. Capacitive and inductive sensors allow metals and other non-metallic materials to be detected, optimizing waste segregation, which reduces operating costs and improves workplace safety by reducing manual intervention. A key aspect of this modernization is the integration of the Internet of Things (IoT), which transforms the monitoring and control of these systems. Through IoT platforms such as Blynk, it is possible to view data such as the weight and quantity of recycled materials in real time, improving supervision and facilitating quick decisions. The scalability of the system allows efficient recycling management in the face of increasing demands. Key indicators include a reduction in cycle time by 58.3%, a decrease in the error rate between 15-20%, and a classification efficiency of 94.7%. In addition, productivity increased by 73.16%, allowing the classification of 32 pieces per minute, compared to 18.48 for the manual method, and processing capacity grew by 50.8%, reaching 60 kg/hour. Together, automation and IoT offer a comprehensive solution to recycling challenges, improving sustainability and reducing the environmental impact of industrial processes, while optimizing resources.***

Keywords-- Efficiency, Automation, Recycling, IoT.

I. INTRODUCTION

Over time, solid waste generation has experienced exponential growth globally, driven by factors such as increased urbanization and the consumption of short-lived products. According to World Bank projections (2018), it is estimated that by 2050, annual waste production will reach 3.4 trillion tons, which would represent an increase of 70% compared to current levels [1]. Despite advances in waste management technologies, many countries still rely on manual or semi-automatic methods, leading to inefficiencies in the sorting process and exposing workers to risky conditions in unsanitary environments.

This problem, far from being isolated, is reflected in greater magnitude in developing countries, such as Peru, where the situation is particularly challenging. Waste separation and recycling infrastructure remains limited, resulting in a low recovery capacity for recyclable materials and a significant accumulation of waste in landfills. According to data from the Ministry of the Environment, 8,450,715 tons of waste are generated annually in the country, of which only 1.9% is formally recycled [2]. The lack of automated and accurate technology for sorting limits the scope of recycling, as many potentially recoverable materials are not properly separated. In addition, the high costs associated with the implementation of advanced systems, together with the lack of personnel specialized in automated sorting technologies, represent significant barriers to moving towards more efficient and sustainable waste management.

This panorama is also reflected at the local level. A recycling company, with more than ten years of experience in the recycling sector in Lima, faces similar challenges. The company is dedicated to the purchase and sale of scrap metal, as well as the recycling of iron, metals and solid waste, actively contributing to the circular economy in the country. However, the company's material sorting still relies on manual processes, which limits its material recovery capacity and slows down the operation. Given that the recycling company is committed to properly managing metal waste and facilitating its reinsertion into the production system, the implementation of an automated sorting system would not only optimize its processes, but would also contribute to reducing the environmental impact associated with the accumulation of waste and the inefficient use of resources.

II. BACKGROUND

Waste sorting systems have advanced from basic sensors to integrating technologies such as IoT and deep learning. Various studies address these developments, highlighting the achievements and limitations that persist in current methods of automatic waste classification. In the study, basic sensor technologies for waste sorting are explored through the use of humidity and proximity sensors [3]. Capacitive and inductive sensors are used to distinguish metallic from non-metallic materials, taking advantage of the dielectric constant and conductivity as identification parameters. However, their reliance on static thresholds limits their accuracy in applications with material and environmental variability, highlighting the need for more adaptive and scalable sorting solutions for heterogeneous waste environments.

Similarly, they present a systematic review of automatic waste separation systems, focusing on waste identification devices, machine learning algorithms, and datasets used in these systems [4]. Most systems lack adaptability in real-world environments and rely on limited data, which affects accuracy in identifying complex materials. In addition, the lack of data integration from various sensors reduces their effectiveness in uncontrolled environments.

While previous studies focus on proximity sensors, explore the use of shortwave infrared spectroscopy (SWIR) using discrete LEDs to identify specific materials [5]. This technique achieves 97% accuracy in materials such as plastics and glass, although it presents challenges in materials with complex reflective properties and in varying environments.

Expanding the scope of monitoring technologies, they investigate the use of IoT in waste management. They use RFID systems and wireless sensor networks (WSNs) to identify and monitor containers in real-time [6]. Although IoT facilitates continuous monitoring, it faces challenges in terms of interoperability and power consumption, limiting its scalability in classification applications.

Recent studies illustrate how deep learning approaches applied to advanced sensors (NIR, CO_2, laser, and RGB cameras) can improve accuracy in sorting plastic waste [7]. However, they also face difficulties in uncontrolled conditions, such as dark or contaminated materials, and require advanced integration to optimize large-scale sorting.

The automation of electronics recycling and industrial waste management are seeing significant advances thanks to the implementation of advanced sensor technologies. Several studies carry out a systematic review of the literature on the circular economy in electrical products, underlining the crucial role of sensors in the automation of recycling [8]. They highlight that the integration of RGB (color) and infrared technology sensors improves the identification and classification of electronic components, allowing a more efficient recovery of valuable materials. A system designed by Baker et al. employs a combination of sensors on a conveyor belt, using deep neural networks such as EfficientNet to analyze images and automatically classify devices. This methodology allows for accurate separation of recyclable and non-recyclable materials, reducing waste and increasing the rate of resource recovery.

Complementing this perspective, they address the challenges of automated robotic sorters for mixed industrial waste. They point out that automatic sorting systems are based on different types of sensors, including optical and thermal techniques. They use near-infrared (NIR) hyperspectral cameras and thermal cameras to sort materials based on surface intensity profiles, allowing for more efficient separation of waste [9]. Thermal sensors, in particular, help identify the composition of objects from extracted features, thus improving the recovery of valuable components in the recycling process.

For their part, they highlight sensor-based monitoring as an essential technology for waste management in smart cities. They explain that solid waste treatment systems include sensors that control parameters such as temperature, humidity, gas and sound in real time [10]. These devices are essential to track the amount of waste generated and evaluate the effectiveness of management strategies. A notable example is the creation of an electronic nose that quantifies the concentration of odors, aiding in wastewater treatment. Infrared sensors are particularly useful for determining the fill levels of waste containers and monitoring noise pollution, contributing to more efficient urban waste management.

Current research complements this view by exploring the use of sensors in smart recycling systems, especially in relation to the circular economy and marine plastics. In their review, they highlight that optical and thermal sensors allow the accurate detection of plastic waste in different environments, facilitating automatic waste sorting and optimizing material separation. Near-infrared (NIR) sensors are effective in identifying different types of polymers, improving recycling efficiency and contributing to the sustainability of waste management systems [11].

Finally, they review the use of optical sensors and machine learning algorithms in the characterization of the material flow for mechanical recycling processes. They highlight that the accurate identification of materials using advanced sensors, such as near-infrared and hyperspectral imaging, optimizes both the quality and quantity of recycled materials [12].

They explain that membrane technologies have emerged as advanced options for wastewater treatment due to their ability to remove contaminants and recover resources in a sustainable manner [13]. However, challenges such as membrane fouling persist, affecting system performance. To address this problem, the use of artificial intelligence (AI) models that optimize the treatment process, predict yields, and establish ideal operating conditions is proposed, highlighting the potential of AI to improve the efficiency of membrane technologies.

In addition, they emphasise the importance of improving plastic packaging recycling in Austria in order to meet EU recycling targets [14]. In this context, they propose an improvement in the recovery of plastics through the automated sorting of municipal solid waste (MSW) in treatment plants, in order to maximise the amount of plastic recycled before incineration. This streamlined approach can help Austria achieve its environmental goals by leveraging mixed MSW as a source of recyclable materials.

On the other hand, they investigate the implementation of digital twins in water resource recovery facilities, particularly at a plant in Eindhoven, the Netherlands. Digital twins allow you to monitor and simulate plant operation in real-time, aiding in decision-making, predictive maintenance, and process optimization [15]. With an automated data infrastructure and an interface developed in collaboration with operators, this system significantly improves plant management and the prevention of operational problems.

They also address the complexity of controlling combustion in large-scale incineration plants due to the variability of solid fuels derived from waste. Through the "AdOnFuelControl" project, they integrate advanced technology, such as 3D scanners and weighing systems, to calculate the calorific value of waste and optimize combustion. This method promises a more efficient and cleaner operation in incineration plants, adapting to the specific characteristics of each type of waste [16].

As mentioned, they develop an open-source IoT framework for real-time control in the e-waste bioleaching process [17]. This system includes an Android app to remotely monitor and manage plant status, enabling rapid response to issues and optimizing resource usage. With an adaptable interface that sends real-time alerts, this system contributes to greater efficiency, safety and sustainability in the recycling of valuable metals, promoting the reduction of the environmental impacts of e-waste.

Therefore, they propose a hybrid model of deep learning and transfer to improve waste sorting and promote environmental sustainability. Using convolutional neural networks (CNNs) and Bi-LSTMs, the study focuses on categorizing organic and recyclable waste with high accuracy, reaching 96.78% in multiclass classification and 98.25% in binary classification. These results outperform other models by reducing the mean squared error rate to 0.01297 and 0.01104 respectively [18]. The use of advanced techniques, such as Bayesian optimization, demonstrates the model's ability to improve waste management in a sustainable and efficient manner.

Finally, they analyze digitalization in waste recycling as a key strategy to optimize waste management and move towards a circular economy. Through a bibliometric study of 678 documents, the authors identify that digital applications have facilitated the classification and collection of waste through technologies such as IoT and artificial intelligence. These developments not only improve efficiency in the supply chain but also promote sustainable practices in smart cities [19].

III. PROPOSAL

In recent years, the recycling industry has faced various challenges in the classification of materials, with multiple proposals that have sought to improve the efficiency of these processes. However, many of these initiatives have shown limitations in their ability to adapt to varied environments and deficiencies in the accuracy of identifying complex materials. In addition, these solutions have often relied on technologies that do not provide the monitoring and control required for waste sorting.

Against this backdrop, our proposal focuses on optimizing efficiency in the sorting of recyclable materials in the Recycler through an innovative approach that integrates the Internet of Things (IoT). Unlike other more traditional methods, which in some cases even require manual intervention, our automated system radically transforms the management of the sorting process. By developing our mobile app, operators will have instant access to key data such as the amount and weight of recycled materials, allowing them to make informed and agile decisions.

In addition, this mobile application will allow users to monitor and control the system remotely with a simple on/off button. This feature not only improves automation, but also sets a new standard in industrial process management. Therefore, we conclude that by combining IoT technologies with Arduino-controlled automation, our project not only seeks to move towards sustainability, but also responds to the growing need for innovative solutions in the recycling industry in the face of today's environmental challenges.

Objective

Optimize the process of sorting recyclables in a recycling plant by implementing automated technology, with the purpose of increasing efficiency, reducing operating costs, and improving occupational safety.

IV. METHODOLOGY

The methodology followed in this study is based on the iterative prototyping process, which allows the construction, testing and continuous improvement of an automated classification system for recyclable materials. This approach was developed in four main stages.

Design and Modeling

The development of the prototype began with the creation of the drawings of the main components in 3D, components such as the rails that were designed to connect to three servo motors. These rails allow for automatic separation of materials. Each object passes through the conveyor belt and once it is identified by a sensor, the system activates the rail to push the object into the corresponding container. The blueprints provided a basis for precise assembly of the prototype. However, in some cases, adjustments had to be made to some parts to ensure that each component works in a coordinated manner within the automated system.

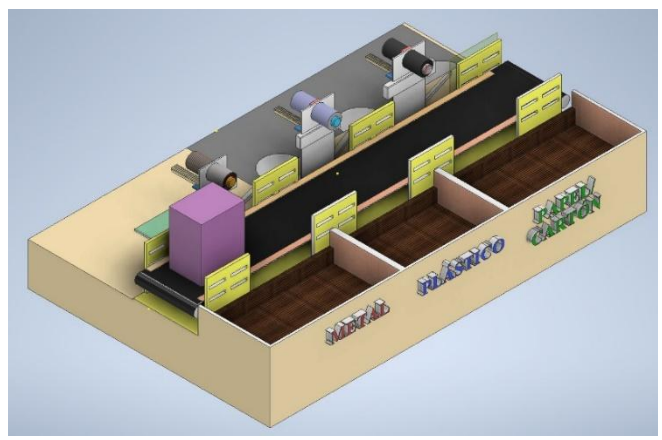

Fig. 1 Model of the prototype in Inventor 3D

The following fig. shows the model plan of the prototype of the recyclable materials sorter. This design will serve as the basis for future printing and construction of the physical model, detailing the dimensions and layout of each component. This drawing will provide an initial guide for assembly and allow for the necessary testing to adjust the prototype to achieve functional waste sorting objectives.

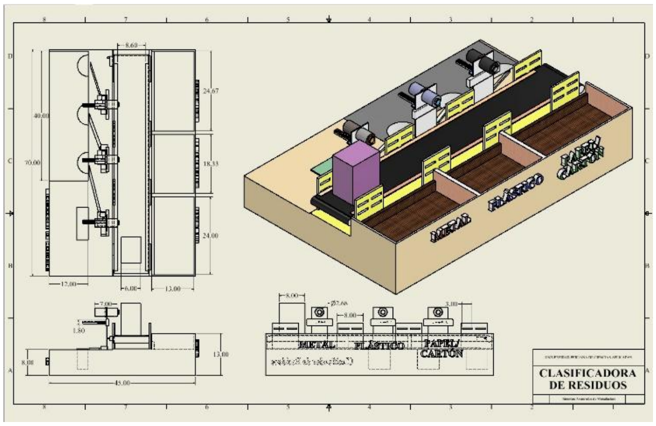

Fig. 2 3D Prototype Model

Prototype Assembly

The assembly process of the prototype of the recyclable materials sorter is detailed below. This system has been designed by integrating several key components, each with a specific function in the sorting process. The following table presents a description of the components used, including sensors, control modules, and the central processing system, which together enable efficient material detection and sorting. The careful selection of these components ensures the operability of the prototype and lays the foundation for future system optimizations.

TABLE I
PROTOTYPE ELEMENTS

Prototype Elements	
Component	***Description and use***
Arduino UNO R4 Wi-fi	Microcontroller with built-in Wi-Fi capabilities, enabling wireless connectivity. It is the brain of the system, in charge of controlling the sensors, actuators, the load cell, and communicating with the Blynk platform to send the data to the mobile application.
Cable multiconductor	It is used to connect the different components of the system (sensors, servos, modules) to the Arduino, facilitating the transmission of signals and power.
Inductive sensor	Detects metal objects without physical contact, measuring changes in electromagnetic fields.
Capacitive sensor	It detects non-metallic objects, such as plastics or cardboard, by measuring the variation in electrical capacitance.
HX711 Load Cell & Module	The cell measures weight, and the HX711 module is a specialized ADC converter for working with load cells.
3D Linear Actuator	Converts rotary motion to linear motion.
Conveyor belt	By which the recyclable materials are moved to the sensors, where they will be identified and classified.
Servomotor	Used to drive mechanisms that redirect materials into their sorting compartment.
Prototype Elements	
Component	***Description and use***
LCD Screen	Displays relevant information such as the quantity of sorted materials and the weight of the metal detected.
L298N Module - H-Bridge	Allows you to reverse the direction of the conveyor belt or control the movement of other motors in the system.
Power Supply 12V-1.5A	It provides the necessary energy for the electrical components of the system (motors and the conveyor belt).
LM2596 Module	Motor controller that allows you to control the movement of DC motors or actuators. It also controls the conveyor belt motor, allowing it to move when the system is in operation.

The prototype structure was built using MDF as the main material, selected for its strength and ease of handling. Each piece was precisely cut using a laser cutter, which ensured that the edges were accurate and allowed for a clean and stable assembly. This laser cutting process was essential to maintain uniformity in each of the parts of the structure.

To achieve this, a detailed drawing was generated in AutoCAD, where the exact measurements of each component were specified. This blueprint served as the basis for the laser cutting, allowing each part to fit perfectly into the final prototype design. The precision in the design and cut facilitated assembly and ensured that the structure had the required stability and functionality, thus optimizing the effectiveness of the prototype in its subsequent stages of implementation.

In addition, wood and acrylic were used in the support bases for the sensors, ensuring the stability and precision of their positioning. The wood was fixed to the base of the model with screws to provide greater durability and firmness.

In addition, to improve the organization and presentation of the prototype, ducts were used, which allow an orderly and safe handling of the cables coming from the conveyor belt motor, the sensors and the control modules. This system not only brings a cleaner look to the model, but also facilitates future interventions and technical adjustments, improving accessibility and safety in cable handling.

In order to guarantee the safety and correct operation of the prototype, various preventive and orientation signs were incorporated. Among these, hazard warnings were added, including 'Do not approach', 'No water' (due to the presence of electrical components), and 'High voltage' warnings, with the aim of minimizing risks during the operation and observation of the system. In addition, direction signaling was installed on the conveyor belt to indicate the direction of movement, thus facilitating the proper flow of materials and understanding the operation of the prototype.

To improve the accuracy and efficiency of the sorting process, alignment mechanisms were incorporated into the conveyor belt, which guide the material along its path. These mechanisms are made up of small arms of light wood that act as diverters, correcting the position of the material as it moves through the belt. This design allows each object to be kept in a stable and centralized position, making it easier for the sensors to detect and classify the materials more accurately, avoiding irregular displacements or accumulations along the way.

The implementation of these adjustment arms responds to the 'Poka Yoke' philosophy, an error control approach that seeks to eliminate potential problems from the initial stage of the process. In this way, the sorting system benefits from a more organized and uniform route, reducing the need for manual intervention and minimizing the possibility of errors in material detection. These alignment mechanisms not only optimize conveyor belt operability, but also contribute to a more reliable and efficient sorting process.

It is worth mentioning that the weight of the sorted material is a crucial piece of information in recycling plants, as it allows for efficient management of resources and optimization of the storage, transport and marketing processes of recyclable materials. Having load cells that record the weight of each type of sorted material provides valuable information for calculating processing capacity and evaluating system performance. This type of measurement is essential for establishing the commercial value of materials and determining the logistics required for their handling in large volumes.

In this prototype, a load cell has been implemented that, in this experimental phase, is used to weigh the sorted metal. This feature, in addition to providing specific data for analysis, demonstrates the feasibility of integrating additional load cells for other materials, such as plastic and paper/cardboard, in order to create a detailed and accurate record of the weight of each type of waste. This approach not only contributes to the comprehensive analysis of process efficiency, but also lays a foundation for the implementation of a more efficient weighing system.

Below is a diagram that provides a clear view of the system architecture, making it easier to analyze the data flow and the interaction between components.

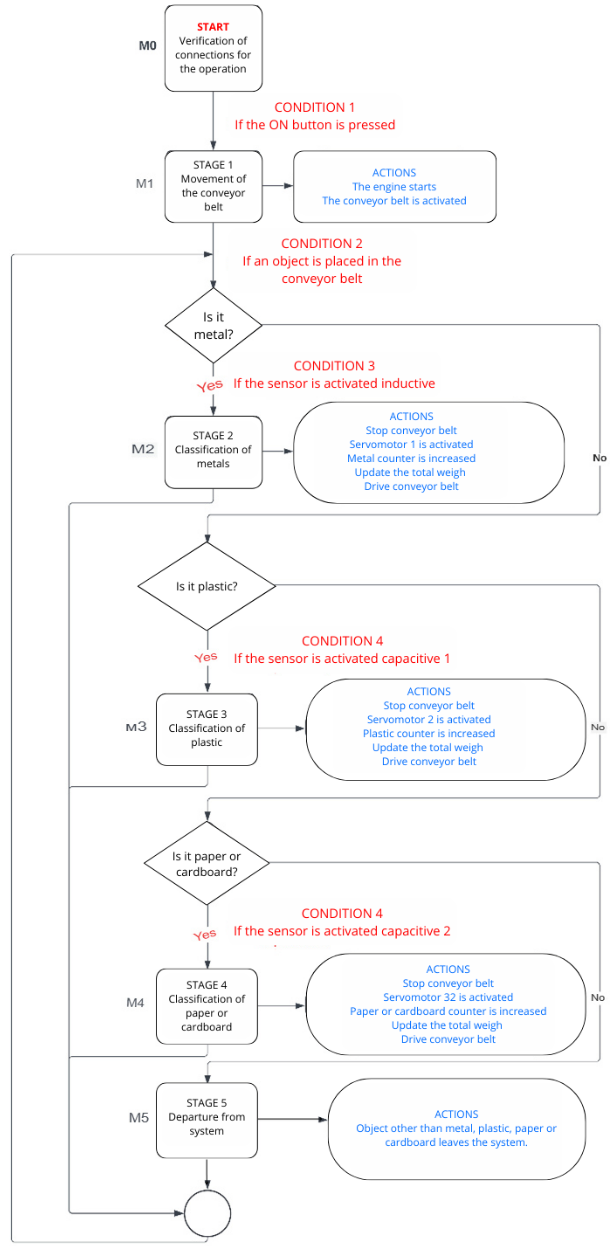

Fig. 3 Diagram of States

Programming in Arduino

The classification logic and sensor configuration were programmed into the Arduino IDE. Sensors detect the type of material based on set thresholds and activate servo motors to direct waste to the appropriate container. Similarly, the LCD screen displays real-time system data optimizing user interaction with the system and visual feedback.

This code presents the initial configurations for connecting and controlling the electronic components that make up the waste sorting system. The WiFi credentials necessary for connectivity through Blynk are defined, allowing remote monitoring and control of the prototype. In addition, essential libraries such as WiFiS3.h, BlynkSimpleWifi.h, LiquidCrystal_I2C.h, Servo.h and HX711.h are included for managing the LCD screen, servo motors and the weight sensor.

The constants and variables that make up the HX711 load cell are set, including the calibration value and connection pins (DOUT and CLK), as well as the pins assigned to each sensor and module on the Arduino Uno R4. These elements form the basis of the system, allowing the detection and classification of materials, as well as the visualization of data in real time through the LCD screen.

This initial configuration code is critical to the operation of the prototype as it defines the structure and resources required for programming the classification logic, which is detailed in the following sections.

The code shows the control logic for the conveyor belt and servo motors of the sorting system. The start variable determines whether the belt is in operation, setting the speed to 52% when activated. Pins IN1 and IN2 control the direction of the belt, allowing movement in the desired direction.

When the sensor detects a material (SENSOR1 or SENSOR2), the system temporarily stops the belt (0% speed) and activates the corresponding servo motor. The servo motor rotates 135 degrees to open the gate, allowing the sorted material to be redirected to the proper container. After a short pause, the servo motor returns to its initial position to close the gate and resume belt movement.

IOT Implementation

Next, the role of the Internet of Things (IoT) in the waste sorting system is addressed. The integration of IoT allows the connection and remote monitoring of components, facilitating real-time data collection and remote control of the prototype. Through the Blynk platform, the data generated by the sensors and modules is transmitted directly to an interface accessible from mobile devices and the web, optimizing user interaction and improving responsiveness to any eventuality in the system. This connectivity is essential to transform the prototype into an intelligent solution, adapted to the automation and efficiency needs of modern recycling plants.

The image shows the configuration of the Blynk app used for real-time monitoring of the waste sorting system, available on both the mobile app and the web platform. On the dashboard, widgets have been config. d to visualize the data obtained from the sensors, including the amount of sorted materials (metal, plastic, and paper) and the weight of the waste (in kg). The main switch (RUN/ STOP) allows the system to be activated or stopped remotely.

Each type of sorted material is assigned a specific value on the Blynk virtual pins (V1 for metal, V2 for plastic, V3 for paper, and V4 for weight), making it easy to monitor each category independently. This interface design provides the user with an intuitive and accessible experience, optimizing system monitoring and allowing effective control of the prototype from any device with access to the application.

In short, the IoT transforms this model into a smart solution that goes beyond a mechanical system, providing it with data collection and remote management capabilities that are essential in the modern era of Industry 4.0. IoT integration not only contributes to sustainability and reduced operating costs, but also lays the foundation for the development of more efficient and sustainable recycling systems.

Indicators

To ensure the effectiveness and reliability of the material classification system, a series of key indicators were established to measure its performance in operating conditions. The indicators and formulas used to evaluate the system's performance are based on standard metrics widely applied in industrial engineering and quality management literature [20]. These metrics allow for a systematic assessment of process efficiency, accuracy, and operator productivity under real operating conditions. The selected indicators include:

Cycle Time

Importance: It allows you to identify how efficient the manual process is and how many materials can be sorted per unit of time.

$$\frac{Total\ sorting\ time}{Amount\ of\ sorted\ materials} \quad (1)$$

Objective: Reduce cycle time through workflow optimization or improved operator skills.

Error rate

Importance: A high level of errors can lead to additional costs, delays, and waste, which affects the productivity and quality of the process.

$$\frac{Number\ of\ misclassified\ materials}{Total\ materials\ classified}\ x\ 100\% \quad (2)$$

Objective: To minimize the error rate before automation, detecting the main causes of errors.

Sorting Efficiency

Importance: Crucial in automated sorting systems for recyclable materials, as high reliability ensures that materials are properly processed at later stages, such as recycling or reuse.

$$\frac{Amount\ of\ materials\ correctly\ classified}{Total\ materials\ classified}\ x\ 100\% \quad (3)$$

Objective: To increase sorting efficiency through the automation of the waste sorting process.

Productivity

Importance: A low level of productivity indicates bottlenecks, lack of training, or work overload, which justifies the need for automation.

$$\frac{Number\ of\ classified\ materials}{Number\ of\ operators} \quad (4)$$

Objective: To increase the quantity of sorted materials without increasing the number of errors or compromising quality.

Rework Rate

Importance: Missorted materials waste time and resources, indicating problems in process quality.

$$\frac{Number\ of\ materials\ reprocessed}{Total\ materials\ classified}\ x\ 100\% \qquad (5)$$

Objective: Reduce rework to improve overall process efficiency and quality.

Process Capacity

Importance: It is useful to assess whether the current manual process is reaching its maximum capacity or if there are limitations in human and physical resources that impede growth.

$$\frac{Max.quantity\ of\ classified\ materials}{Available\ time} \qquad (6)$$

Objective: To identify process constraints and establish a baseline for measuring capacity gains following automation.

These indicators will be used as reference parameters in validation tests, allowing a comprehensive evaluation of the accuracy, efficiency and robustness of the system in its operation.

Testing and Validation

To evaluate the functionality and efficiency of the waste sorting system, controlled tests were carried out under simulated conditions. These tests focused on measuring key indicators such as classification accuracy, classification time, error rate, and system responsiveness in various operational scenarios.

During the tests, scenarios were executed that simulate the real flow of materials in a recycling plant, recording the performance of the system against different types of waste. These scenarios included variations in the speed and quantity of materials on the conveyor belt to assess the consistency and reliability of the prototype.

The selected evaluation indicators make it possible to determine whether the system meets the expected standards of accuracy, efficiency and safety. By obtaining a comprehensive view of operation under controlled conditions, a solid foundation is established for analyzing performance in real-world operating situations.

Below is a flowchart illustrating how the material sorting system works. This diagram provides an overview of the stages and decisions involved in the sorting process, making it easier to understand the operating logic of the system.

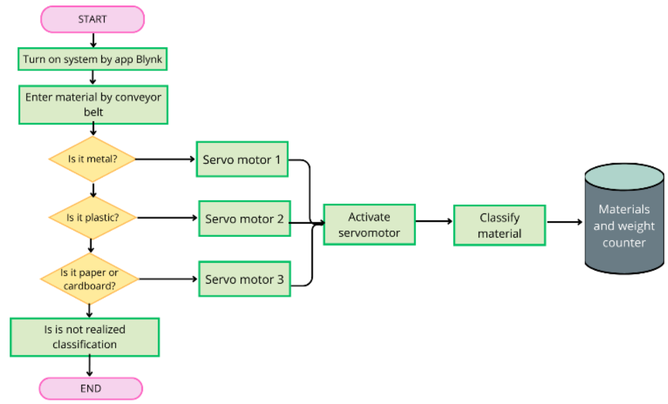

Fig. 4 Performance Flow Chart

V. Results

The results obtained by comparing the manual sorting process with the proposed automated system are presented below. Various key indicators, such as cycle time, error rate, sorting efficiency, productivity, rework rate and process capacity, were evaluated, which reflect the impact of automation on improving accuracy, speed and production capacity. These results allow us to analyze in detail the advantages of the implementation of the automated system and its effectiveness in optimizing the performance of the sorting process.

TABLE II
RESULTS OBTAINED

Indicators	Results		
	Manual process	Prototype	Improvement /reduction
Cycle Time	4.50 sec/piece	1.88 sec/piece	58.3%
Error rate			
Metal	25%	5%	20%
Plastic	23%	8%	15%
Paper	19%	3%	16%
Sorting Efficiency	77.7%	94.7%	21.89%
Productivity	18.48 piece/min	32 piece/min	73.16%
Rework Rate	14.0%	7.7%	45.24%
Process capacity	39.78947 368	60	50.8%

Indicators

The results obtained demonstrate a notable improvement in the performance of the automated system compared to the manual process in different key indicators.

In terms of cycle time, calculated as shown in (1), the automated prototype achieves a reduction of 58.3%, sorting parts in an average of 1.88 seconds, compared to 4.5 seconds for the manual method.

The error rate, derived from (2), also decreases considerably in each type of material (metal, plastic and paper), with reductions of 20%, 15% and 16% respectively, which highlights an improvement in the accuracy of the classification.

Sorting efficiency, based on (3), reaches 94.7% with the automated system—an increase of 21.89% over the manual process—suggesting greater accuracy and reliability in material identification.

Productivity, computed using (4), increases by 73.16%, reaching a sorting capacity of 32 parts per minute compared to 18.48 pieces per minute for the manual process.

As for the rework rate, it is also reduced from 14% to 7.7%, decreasing the need for additional classifications.

Finally, the processing capacity in the automated system, by allowing continuous operation of 24 hours, reaches 60 kg/hour, in contrast to the 39.8 kg/hour of the manual process. This represents an increase of 50.8%. These results confirm that the automated system is not only more efficient and accurate, but also enables handling higher production volumes, effectively responding to operational demands.

Furthermore, the implementation of the automated sorting system contributes to improving operational safety in the recycling process. By reducing manual handling of materials and minimizing operator involvement in repetitive or potentially hazardous tasks, the system lowers the likelihood of workplace accidents and fatigue-related errors. Recent studies emphasize that automation technologies—such as sensor-based systems and programmable controls—can significantly reduce workers' exposure to unsafe conditions in industrial environments, thus enhancing overall safety [21]. In this context, the system not only increases productivity and accuracy, but also creates a safer working environment for personnel involved in waste management operations.

Economic Viability

This economic analysis aims to evaluate the cost-effectiveness of implementing an automated sorting system in a medium-sized recycling plant. To do this, financial tools such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI) and Payback Period were used. These metrics make it possible to estimate the expected return on the initial investment and evaluate the long-term sustainability of the system, considering both the income generated by the sale of recyclable materials and the savings in labor and other costs.

Initial Investment: The initial investment for the project amounts to $6,531.41, including the acquisition costs of highly durable and reliable industrial components, necessary for continuous operation in a recycling plant environment. This investment covers equipment such as capacitive and inductive sensors, industrial controllers, servo motors, an HMI display for real-time monitoring, and a SCADA monitoring system for supervision and control. In addition, the costs of installation and professional assembly were included, ensuring that the system meets the required quality and safety standards.

Annual Operating Costs: The system requires annual operating costs of $ 1,014.66.00, which mainly include electrical power consumption, preventive and corrective maintenance of components, and the cost of subscription to the SCADA monitoring system. Electrical energy is estimated for a daily consumption of 8 hours of continuous operation, while maintenance considers the calibration and periodic review of sensors and servomotors.

Revenue and Potential Savings: The system generates total annual revenue and savings of $5,589.01 through the sale of recycled materials (metals, plastics, paper/cardboard) and a reduction in labor expenditure by automating the sorting process. The sale of recycled materials is a constant source of revenue for the recycling plant, while the labor savings are due to less human intervention in the process, which optimizes productivity and reduces operating costs.

Calculation of Net Present Value (NPV): The NPV was calculated by applying a discount rate of 10% to reflect the opportunity cost of capital in this project. Projected net annual cash flows ($4,574.00), discounted at this rate over a 5-year period, resulted in a NPV of $10,808.95. This positive NPV indicates that the expected revenues exceed the initial investment, confirming that the project will generate long-term financial benefits and add value to the company.

Calculation of the Internal Rate of Return (IRR): The IRR is the yield that equals the NPV to zero. For this project, the IRR was 64.16%, significantly higher than the 10% discount rate, which indicates an attractive return on investment. This high IRR value suggests that the company will obtain a high return in relation to the initial investment, reaffirming the viability and profitability of the system in a competitive environment.

Return on Investment (ROI) Calculation: The annual ROI was calculated at 70.03%. This value reflects the percentage of the initial investment that is recouped in the form of revenue and savings each year, before discounting operating costs. The ROI highlights the system's ability to generate consistent revenue and demonstrates that the investment will pay off for the recycling company in the short term.

Payback Period: The Payback Period is approximately 1 year and 5 months. This means that, after this period, the annual revenue will begin to represent net profits for the company, once the initial capital invested in the classification system has been recovered. This quick payback period is favorable for the company, as it minimizes financial risk and ensures profitability in the short term.

In sum, the economic analysis shows that the implementation of the automated sorting system is a profitable investment for the recycling plant. The initial investment of $6,531.41.00 will be recouped over a period of approximately

1 year and 5 months, minimizing financial risk and ensuring prompt returns. In addition, the project has a NPV of $10,808.95, an IRR of 64.16%, and an annual ROI of 70.03%, which indicates that the investment generates a return above the opportunity cost of capital (10%) and translates into a considerably attractive rate of return.

These results confirm that the system will not only recoup its initial cost, but also provide significant economic benefits to the company. Over a five-year horizon, a net profit of $22,872 is projected, consolidating this system as a viable and sustainable investment to optimize productivity, reduce costs, and increase revenue through the sale of recycled materials. Overall, this project represents an economically and environmentally sound investment for the company.

The system is designed to grow and adapt easily, making it a flexible solution for different recycling needs. Whether it's a small local center or a larger industrial facility, the setup can be expanded by adding more sensors or adjusting the size of the conveyor belt to handle greater volumes or different types of materials. Since it uses Arduino and a simple mobile app (Blynk), it's easy to monitor and control the system remotely—no need for complex infrastructure or constant supervision. As recycling goals increase or new materials need to be sorted, the system can be upgraded without starting from scratch. This makes it a smart, future-proof solution for any organization looking to improve their recycling process over time.

This work distinguishes itself by offering a concrete, functional, and validated prototype that addresses the specific challenge of recyclable material sorting, combining IoT integration with accessible technologies.

While related studies such as [22] and [23] explore advanced AI- and IoT-based frameworks aimed at broad urban waste management systems, our contribution focuses on a scalable and operational solution, tested in real conditions, and designed to optimize key performance indicators such as efficiency (94.7%), productivity (+73%), and error reduction.

Rather than replacing these broader approaches, our work complements them by bridging the gap between conceptual innovation and hands-on implementation, making automation more viable for medium-scale recycling plants and municipalities with limited resources.

VI. Conclusion

Operational safety is greatly enhanced by automating the sorting process, as it keeps workers away from direct contact with sharp, heavy, or unsanitary materials. Instead of relying on manual handling, the system uses sensors, servo motors, and an Arduino-based controller, all managed through a user-friendly IoT platform (Blynk), which allows the process to be monitored and controlled remotely. This reduces the risk of accidents and makes the operation more efficient and safer. Clear safety signs like "Do not approach" and "High voltage," along with organized cable routing, help prevent electrical hazards. Simple alignment features also keep materials in place, reducing jams and the need for human intervention. Altogether, the system creates a cleaner, safer, and more comfortable environment for workers.

The automated system managed to reduce cycle time by 58.3%, meeting and exceeding the goal of reducing it by at least 50%. This result confirms the greater speed and efficiency of the automated system, with an average of 1.88 seconds per part compared to 4.5 seconds for the manual process.

The system met the goal of reducing errors in material sorting by at least 15%. Error rates decreased by 20% for metals, 15% for plastics and 16% for paper/cardboard, demonstrating a considerable improvement in the accuracy of identification of each type of material.

A sorting efficiency of 94.7% was achieved, exceeding the target of achieving an efficiency of over 90%. This increase reflects the high accuracy and reliability of the system in the correct identification of materials, improving the consistency and effectiveness of the process.

The sorting capacity of the automated system increased by 73.16%, exceeding the target of increasing productivity by at least 50% compared to the manual process. With 32 parts per minute versus 18.48 pieces per minute for the traditional method, the automated system demonstrates its ability to handle higher volumes of work efficiently.

The automated system reduced the rework rate from 14% to 7.7%, meeting the goal of decreasing this rate by at least 30%. This reduction minimizes the need for additional classifications, optimizing workflow and reducing operating costs.

The processing capacity of the automated system increased by 50.8%, reaching 60 kg/hour compared to 39.8 kg/hour for the manual process. This exceeded the target of increasing processing capacity by at least 40%, enabling an effective response to continuous processing demands.

The financial analysis confirmed that the system is profitable and meets the economic objectives. The initial investment of $6,531.41 will be recouped in approximately 1 year and 5 months, reaching the return target in less than 2 years. In addition, the system obtained a Net Present Value (NPV) of $10,808.95 and an Internal Rate of Return (IRR) of 64.16%, well above the minimum target of 20%, which reaffirms its economic viability and attractive profitability.

Together, the automated material sorting system not only streamlines workflow and reduces errors but ensures a solid return on investment and projects sustained profitability. This solution represents a viable and sustainable investment for any recycling operation looking to improve its efficiency and competitiveness in the market.

Finally, this project is distinguished by its clear alignment with the Sustainable Development Goals (SDGs), standing out in the recycling sector for its innovative and automated approach. Unlike other projects, this proposal integrates automation technologies that not only optimize efficiency and accuracy in waste sorting, but also significantly reduce waste, which responds directly to SDG 12: Responsible Consumption and Production. Its innovative design and application of advanced technologies comply with SDG 9: Industry, Innovation and Infrastructure, promoting sustainable infrastructure in industrial recycling.

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