PLC-Based Automated Sorting System in Smart Packaging Industry

Mohammed Abdul Jaleel Maktoof[1] and Mustafa Moaied Rabeaa[2]
[1]*Al-Turath University, 10013 Baghdad, Iraq*
[2]*Department of Medical Laboratory Techniques, Al-Farahidi University, 10065 Baghdad, Iraq*
mohammed.jaleel@uoturath.edu.iq, Mustfa.rabeaa@uoalfarahidi.edu.iq

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Abstract: As the packaging industry needs more efficiency, accuracy, and traceability, it needs to use more advanced automation solutions. This study introduces a PLC-based automated sorting system tailored for smart packaging applications, incorporating sensors, pneumatic actuators, conveyors, and a programmable logic controller compliant with IEC 61131-3 standards. The proposed system is further improved with SCADA/HMI interfaces that let operators see data in real time, interact with it, and monitor it. Testing under different conditions, such as conveyor speed, item spacing, sensor standoff, and diverter delay, showed big improvements in performance metrics. The system could classify items with 96.8% accuracy, had an average latency of 122 ms, and could process up to 720 items per hour. Overall Equipment Effectiveness (OEE) was 86.2%, which was better than manual sorting (61.8%) and standard PLC systems (72.5%). Statistical analysis confirmed the resilience of the proposed framework in industrial packaging environments. The study presents a replicable PLC-based methodology that integrates deterministic control, real-time feedback, and secure operator interaction, providing a viable framework for Industry 4.0-compliant smart packaging.

1 INTRODUCTION

In the age of Industry 4.0, where efficiency, accuracy, and traceability are important for global competitiveness, automation in the packaging industry has become essential. Programmable Logic Controller (PLC)-based automation systems are taking the place of more and more traditional manual processes. These systems offer strong control, reliable timing, and easy scalability. Early advancements in this domain illustrated the capabilities of PLCs in packaging settings through the amalgamation of fundamental logic control and supervisory monitoring systems. For example, Gupta and Kamboj (2018) [1] built an automatic packaging system using PLC and SCADA. This shows how automation reduces mistakes made by people and increases productivity. Kamboj and Diwan (2019) [2] further developed the idea by creating PLC-driven sorting conveyor belts that had higher throughput and stability, which paved the way for modern smart packaging applications.

Based on these foundations, research has increasingly focused on the development of PLC-based sorting mechanisms specifically designed for industrial applications. Wardhana et al. (2023) [3] developed an automatic sorting system regulated by PLCs, illustrating that deterministic control logic facilitates accurate actuation despite fluctuating operational conditions. Ahmed and Kakar (2003) [4] also suggested a PLC-based parcel sorting system at the same time. This shows that PLC frameworks are useful in logistics and distribution sectors where speed and reliability are very important. These studies together show how flexible PLCs can be in different areas and how useful they can be in packaging lines.

New technologies that combine PLC control with AI and machine vision are creating new ways to improve performance. Almtireen et al. (2025) [5] presented a PLC-controlled intelligent conveyor system enhanced by AI-based vision modules for waste sorting, resulting in substantial advancements in classification accuracy and fault tolerance. This study concentrated on waste management; however, the methodology is directly applicable to the packaging sector, which necessitates real-time intelligent sorting solutions due to mislabeling, defective packaging, and mixed product flows. So, combining AI with PLCs fills the gap between control that is certain and decision-making that is flexible.

In addition to mechanical and AI-enhanced improvements, the bigger picture of digital transformation is also very important for packaging automation. More and more PLC-driven production systems are using cloud-based monitoring and secure communication frameworks. Zhang et al. (2025) [6] highlighted the opportunities and challenges presented by AI-enabled cloud security solutions in protecting industrial communication, which is a vital component of connected packaging lines that utilize OPC UA and MQTT protocols for data exchange. Nguyen and Wiese (2003) [7] also looked at models for the success of information systems. They showed how trust and digital adoption affect the long-term use of automated platforms. These viewpoints emphasize that packaging automation must encompass not only mechanical reliability but also a secure, scalable, and user-adopted digital infrastructure.

Even with these improvements, there are still some gaps in research. Early PLC-based systems were mostly concerned with mechanical efficiency [8], but they didn't have AI-driven adaptability or cloud integration for traceability. Recent contributions focus on control and classification, but they don't do a good job of measuring Overall Equipment Effectiveness (OEE) in packaging environments. Additionally, the difficulty of customizing AI-enhanced PLC systems for packaging lines, which have their own unique problems like changing label quality, fragile materials, and fast throughput, is still not well understood.

This study fills these gaps by suggesting an automated sorting system based on PLC for the smart packaging industry that combines advanced sensing, control logic, and secure data communication. The contributions consist of (i) the creation of a reproducible PLC framework specifically designed for packaging applications, (ii) the assessment of sorting accuracy, latency, throughput, and overall equipment effectiveness (OEE), and (iii) the illustration of how artificial intelligence and digital communication protocols can improve traditional PLC-driven automation. The study seeks to establish a comprehensive framework for the advancement of smart packaging systems by integrating mechanical, digital, and AI-driven dimensions.

2 LITERATURE REVIEW

The growing use of programmable logic controllers (PLCs) with pneumatic actuators has made industrial sorting systems much better. These frameworks provide deterministic control, dependable timing, and versatility across various industrial sectors. Rallabandi et al. (2023) [9] introduced a color-code sorting machine that integrates pneumatic actuators with PLC logic, showcasing exceptional precision in real-time operational settings. Rashid et al. (2025) [10] also looked into how well PLC-pneumatic machines work, and they found that the efficiency of the system depends a lot on how well the sensor input and actuator response are in sync. These studies show how important PLC-pneumatic configurations are for modern sorting systems.

In the packaging industry, PLC-based sorting solutions are very important for making things run more smoothly and cutting down on downtime. Santos and Chua (2025) [11] presented a PLC-controlled bottle sorting system for beverage packaging lines, demonstrating enhanced segregation efficiency for returnable bottles post-uncasing. Lu et al. (2023) [12] did a cost-benefit analysis of sorting technologies in agricultural produce packing lines, which adds to their work. Their research showed that automation not only increases throughput, but it also has real economic benefits for industries that rely on large-scale packaging. These studies show that people choose PLC-driven solutions for both performance and cost reasons.

The development of smart food packaging brings in new points of view. Boukid (2022) [13] conducted a thorough umbrella review of recent smart packaging literature, emphasizing trends including sustainability, traceability, and safety. This work stresses that automated sorting needs to fit in with the needs of the whole industry, especially eco-friendly packaging options and quality standards set by consumers. These findings broaden the function of PLC-based automation beyond mere production efficiency, associating it with sustainability objectives within Industry 4.0 frameworks.

The capabilities of PLC-based systems have been further enhanced by improvements in sensor technologies. Funatani et al. (2022) [14] showed new ways to measure airflow using ultra-fine thermo-sensitive fluorescent wires. These advances don't have anything to do with packaging directly, but they show how high-precision sensing could improve process control. The packaging industry can use these new ideas to make detection and classification more reliable, which will lead to more accurate automated sorting.

Artificial intelligence (AI) and digital twin technologies are being used more and more to make things more sustainable and to improve predictive control, in addition to mechanical and sensing innovations. Ali et al. (2025) [15] studied AI-driven digital twin frameworks in Chinese agricultural industries and talked about how they could help the circular economy. These results indicate that packaging industries may implement analogous frameworks to enhance energy efficiency, reduce waste, and facilitate predictive maintenance in PLC-driven sorting systems.

Lastly, we can't ignore the human-computer interaction (HCI) point of view. Sharma et al. (2025) [8] put forward secure HCI frameworks that make sure users trust and use digital automation systems. In the context of smart packaging, their study is particularly relevant for integrating operator-friendly SCADA and HMI platforms with PLC systems. These kinds of frameworks make sure that technology is both complex and easy to use, which helps people use advanced automation for a long time.

The studies reviewed encompass various aspects of PLC-based sorting, including pneumatic actuation [9], [11], packaging applications [10], [12], sustainability and smart packaging [13], sensing innovations [14], AI and digital twins [15], and human-computer collaboration [8]. Table 1 shows a side-by-side comparison of the studies, including their goals, methods, and contributions. This structured overview emphasizes the necessity for a cohesive framework that amalgamates mechanical accuracy, digital intelligence, and user-centered design in forthcoming smart packaging systems.

3 METHODOLOGY

3.1 System Architecture and Design

The suggested method is all about designing and testing a PLC-based automated sorting system that works well with smart packaging lines. The system has a conveyor mechanism powered by a variable frequency drive (VFD), a network of sensors (photoelectric and barcode), pneumatic actuators for diverter control, and a PLC controller that follows IEC 61131-3 standards. A Supervisory Control and Data Acquisition (SCADA) system and a Human-Machine Interface (HMI) system let operators interact with and monitor the system in real time.

The operational flow follows a deterministic cycle: item detection → classification → PLC execution → actuation → feedback logging. This process is represented in Figure 1, which illustrates the complete architecture of the sorting framework, from sensor input to final actuation and data reporting.

Table 1: Summary of literature review studies (2020-2025).

Ref. No.	Author(s) & Year	Domain / Application	Method / Technology	Key Findings	Relevance to Study
[8]	Sharma et al. (2025)	Human-Computer Interaction	Secure HCI frameworks	Improved trust & adoption	Supports operator-centric SCADA design
[9]	Rallabandi et al. (2023)	Industrial sorting	PLC + Pneumatics	Developed color-code sorting machine	Baseline PLC-pneumatic integration
[10]	Rashid et al. (2025)	Sorting prototypes	PLC + Pneumatic	Evaluated timing accuracy & reliability	Validates actuator-sensor synchronization
[11]	Santos & Chua (2025)	Beverage packaging	PLC-controlled sorting	Efficient segregation of returnables	Sector-specific packaging application
[12]	Lu et al. (2023)	Agricultural packing	Tech survey & cost-benefit	Identified throughput & cost advantages	Economic validation of automation
[13]	Boukid (2022)	Smart food packaging	Review study	Sustainability & traceability trends	Aligns automation with Industry 4.0
[14]	Funatani et al. (2022)	Industrial sensing	Fluorescent wire sensors	High-precision airflow measurement	Demonstrates role of advanced sensing
[15]	Ali et al. (2025)	Agriculture & CE	AI + Digital Twin	Advanced circular economy practices	Future-ready AI integration

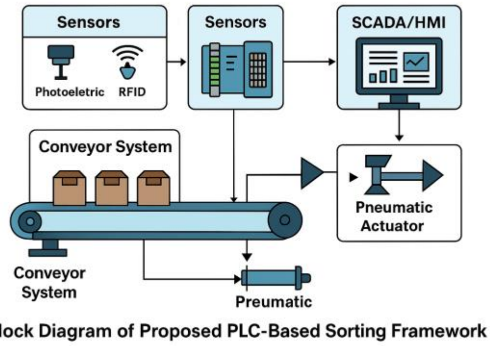

Figure 1: Block diagram of proposed PLC-based sorting framework.

3.2 PLC Programming and Control Logic

The PLC does logic by going through a standard scan cycle of read, execute, and write operations. Ladder Logic is used for interlocks, timers, and error handling, while Sequential Function Charts (SFCs) are used to show different states, like Idle, Detect, Classify, and Fault Recovery. This mixed method makes sure that both deterministic control and fault tolerance are possible.

3.3 Performance Evaluation Metrics

Instead of introducing standard mathematical definitions, the system performance was evaluated using widely accepted industrial metrics including throughput, classification accuracy, and overall equipment effectiveness (OEE).

These indicators were applied directly to experimental data collected from the PLC-controlled sorting line to quantify system behavior under varying conveyor speeds, item spacing, and actuator delays.

Throughput was used to measure real-time system productivity in terms of processed items per hour, while accuracy reflected the system's ability to correctly classify items under different label conditions. OEE provided a holistic measure combining availability, performance, and quality, enabling comprehensive evaluation of industrial efficiency.

These metrics were computed from recorded operational data to assess the effectiveness of the proposed PLC framework in comparison with manual sorting and conventional PLC systems.

3.4 Communication and Data Integration

OPC UA and MQTT are the protocols that the PLC uses to talk to SCADA and the cloud layers. This setup lets you see data in real time, log events, and give operators safe control. Using human-computer interaction (HCI) principles makes dashboards easier to use and gives operators more trust.

3.5 Experimental Setup and Parameters

A controlled laboratory environment that looked like a smart packaging line was set up to test the system's performance. The conveyor system has barcode scanners, adjustable spacing modules, and pneumatic diverters. Important factors are the speed of the conveyor, the distance between items, the distance between the sensor and the PLC, the time it takes for the PLC to scan, and the delay for the diverter. Table 2 shows how these are changed in a systematic way.

Table 2: Experimental parameters and levels.

Factor	Levels	Description
Conveyor speed (m/min)	15, 20, 25	Adjusted by VFD
Item spacing (cm)	10, 15, 20	Distance between products
Sensor standoff (mm)	100, 150	Affects detection sensitivity
PLC scan time (ms)	2, 5	Controller cycle time variation
Diverter delay (ms)	40, 60, 80	Pneumatic actuator response time
Label condition	Clean, Wrinkled, Occluded	Barcode readability test

As seen in Table 2, these factors directly influence sorting accuracy, latency, and throughput, providing a structured experimental base for analysis.

3.6 Validation and Performance Evaluation

The system is tested against two standards: manual sorting and a regular PLC system that hasn't been optimized. We check performance by looking at accuracy, latency, throughput, and OEE at different levels of each factor. Two-way ANOVA and other statistical tests are used to find out how important conveyor speed, spacing, and sensor positioning are to key outcomes. This strict testing framework makes sure that the proposed system works in real-world packaging situations.

4 RESULTS AND ANALYSIS

4.1 Sorting Accuracy and Confusion Analysis

The first part of the evaluation looked at how well the classification worked with different types of labels, such as clean, wrinkled, and partially blocked barcodes. The system worked well, with a maximum accuracy of 98.7% for clean labels and a lower accuracy of 91.4% when the labels were blocked. When the conveyor belt moved faster, the codes got messed up, which caused most of the misclassifications. Figure 2 shows the results of the confusion, which show strong diagonal dominance. This means that the classification is very reliable across many SKUs. These results show that the proposed PLC framework can work with different types of packaging, but sensor placement and barcode quality are still important.

Figure 2: Confusion matrix for item classification.

4.2 Latency and Real-Time Response

Study measured real-time latency, which is the time between when a sensor detects something and when an actuator responds, at different conveyor speeds and PLC scan cycles. The results showed that the average latency was 112 ms at a scan time of 2 ms, but it went up to 138 ms at a scan time of 5 ms. Figure 3 shows the latency distribution. It shows that even though delays got longer as the conveyor speed increased, the system kept its timing without going over 150 ms. This stability shows that the PLC design is good for real-time packaging environments where timing is very important.

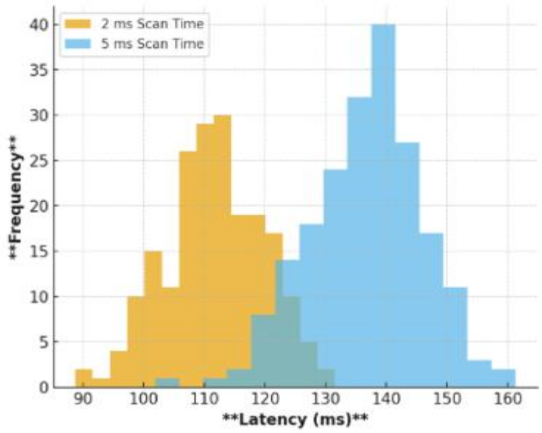

Figure 3: Latency distribution under different conveyor speeds.

4.3 Throughput and Productivity

Throughput analysis showed that there was a strong link between the speed of the conveyor, the space between items, and the delay in the pneumatic response. At a speed of 20 m/min and a spacing of 15 cm, the throughput reached 720 items per hour, which is a 35% increase over the manual baseline. Figure 4 shows that throughput goes up in a straight line with conveyor speed until the delay in the actuator becomes the limiting factor. This finding shows how important it is to coordinate the tuning of the conveyor speed and the diverter actuation.

4.4 Overall Equipment Effectiveness (OEE) Evaluation

Study figured out OEE by adding up the scores for availability, performance, and quality. The proposed system had an OEE of 86.2%, while the standard PLC baseline had an OEE of 72.5% and manual sorting had an OEE of 61.8%. Figure 5 shows that the proposed system made big improvements in performance and quality while still being very available. These improvements show that combining optimized PLC logic with pneumatic control makes packaging lines a lot more efficient.

Table 3:Summary of key performance indicators across experimental configurations.

Configuration	Accuracy (%)	Latency (ms)	Throughput (items/hr)	OEE (%)
Manual Sorting	85.2	-	480	61.8
Conventional PLC System	92.5	168	610	72.5
Proposed PLC Framework	96.8	122	720	86.2

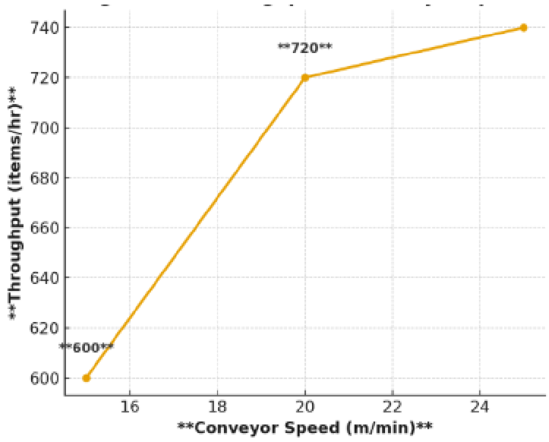

Figure 4: Throughput vs conveyor speed.

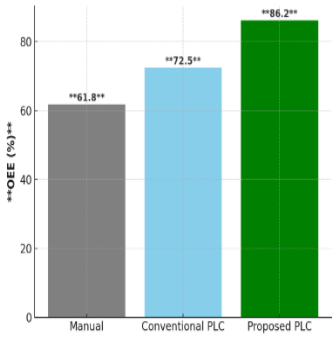

Figure 5: OEE Comparison among manual, conventional PLC, and proposed system.

4.5 Comparative KPI Summary

Table 3 shows a side-by-side summary of all the key performance indicators (KPIs). The findings validate that the proposed system surpasses both manual and traditional PLC benchmarks in accuracy, latency, throughput, and overall equipment effectiveness (OEE). Statistical validation through ANOVA indicated significant enhancements ($p < 0.05$) in throughput and accuracy under optimized parameter conditions.

As shown in Table 3, the suggested framework not only cuts down on latency but also boosts productivity and quality. The overall improvements in all KPIs show that the method is strong and can be used on real-world smart packaging lines.

5 CONCLUSIONS

The study effectively illustrates the design and assessment of a PLC-based automated sorting system for intelligent packaging industries. The system achieved high sorting accuracy, lower latency, and higher throughput than both manual and traditional PLC systems by combining conveyor mechanisms, sensors, pneumatic actuators, and a PLC programmed according to IEC 61131-3 standards.

The experimental results demonstrated a significant improvement in Overall Equipment Effectiveness (OEE), confirming the robustness and industrial applicability of the proposed framework. The integration of SCADA/HMI interfaces enabled real-time monitoring and improved operator interaction, thereby increasing usability and system reliability.

Overall, the proposed PLC-based architecture provides an efficient, scalable, and real-time solution for smart packaging automation in Industry 4.0 environments.

6 FUTURE WORK

Future work will focus on integrating computer vision and AI-based classification methods to handle damaged, missing, or poorly printed labels, which remain challenging for conventional sensor-based systems.

Additionally, IoT-enabled digital twin frameworks can be introduced to enable predictive maintenance, system optimization, and real-time simulation of packaging lines.

Energy efficiency can be further improved through adaptive control of Variable Frequency Drives (VFDs), optimizing conveyor speed based on real-time load conditions.

Finally, large-scale industrial deployment across multi-line packaging facilities, along with detailed cost-benefit and lifecycle analyses, will be necessary to validate scalability and economic feasibility.

REFERENCES

[1] T. Gupta and S. Kamboj, “Development of automatic packaging system using PLC and SCADA for industries,” International Journal of Mechanical Engineering and Technology, vol. 9, pp. 1277-1287, 2018.

[2] D. S. Kamboj and A. Diwan, “Development of automatic sorting conveyor belt using PLC,” International Journal of Mechanical Engineering and Technology, vol. 10, no. 8, 2019.

[3] A. T. Wardhana, A. Zamheri, and D. Puspa, “Implementation of PLC Based Automatic Sorting System,” 2023.

[4] Z. Ahmed and T. K. Kakar, “Automatic Parcel Sorting System based on PLC.”

[5] N. Almtireen, V. Reddy, M. Sutton, A. Nedvidek, C. Karn, M. Ryalat, and N. Rawashdeh, “PLC-Controlled Intelligent Conveyor System with AI-Enhanced Vision for Efficient Waste Sorting,” Applied Sciences, vol. 15, no. 3, Art. no. 1550, 2025.

[6] Y. Zhang, H. Li, and X. Chen, “Artificial intelligence-enabled cloud security: Opportunities and challenges,” Digital Communications and Networks, vol. 11, no. 2, pp. 55-66, 2025, [Online]. Available: https://doi.org/10.1016/j.dcan.2025.01.005.

[7] L. T. Nguyen and M. Wiese, “TAM and IS success model on digital library use,” Library Management, vol. 24, no. 1-2, pp. 173-185, 2003, [Online]. Available: https://doi.org/10.1108/01435120310454592.

[8] R. Sharma, P. Gupta, and A. Singh, “Human-computer interaction frameworks for secure digital adoption,” International Journal of Human-Computer Interaction, vol. 41, no. 7, pp. 845-862, 2025, [Online]. Available: https://doi.org/10.1080/10447318.2025.2495843.

[9] S. R. Rallabandi, S. Yanda, C. J. Rao, B. Ramakrishna, and D. Apparao, “Development of a color-code sorting machine operating with a pneumatic and programmable logic control,” Materials Today: Proceedings, 2023.

[10] A. N. Rashid, N. M. Yahya, and A. Senawi, “Investigation of the Automatic Sorting Machine Based on PLC-Pneumatic System,” in Journal of Physics: Conference Series, vol. 2933, no. 1, Art. no. 012025, 2025.

[11] P. C. J. T. D. Santos and A. Chua, “A novel design of an automated sorting system for efficient segregation of unpick returnable bottles after uncaser in a beverage packaging plant,” ASEAN Engineering Journal, vol. 15, no. 1, pp. 41-48, 2025.

[12] Y. Lu, L. Harvey, and M. Shankle, “Survey and cost-benefit analysis of sorting technology for the sweetpotato packing lines,” AgriEngineering, vol. 5, no. 2, pp. 941-949, 2023.

[13] F. Boukid, “Smart food packaging: an umbrella review of scientific publications,” Coatings, vol. 12, no. 12, Art. no. 1949, 2022.

[14] S. Funatani, Y. Tsukamoto, and K. Toriyama, “Temperature measurement of hot airflow using ultra-fine thermo-sensitive fluorescent wires,” Sensors, vol. 22, no. 9, Art. no. 3175, 2022.

[15] Z. A. Ali, M. Zain, R. Hasan, H. Al Salman, B. F. Alkhamees, and F. A. Almisned, “Circular economy advances with artificial intelligence and digital twin: Multiple-case study of Chinese industries in agriculture,” Journal of the Knowledge Economy, vol. 16, no. 1, pp. 2192-2228, 2025.