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Development of a PLC-Based Automated Bottling and Capping System for Enhanced Production Efficiency

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Abstract

Within the beverage manufacturing sector, manual operations often slow down production and lead to inconsistent product quality. To mitigate these operational boundaries, this investigation focuses on the engineering, construction, and empirical assessment of an automated system designed specifically to control fluid dispensing and container sealing in a set sequence. The core control architecture utilizes an OMRON CP1L-EM Programmable Logic Controller (PLC) integrated with an OMRON NS5-SQ11-V2 Human-Machine Interface (HMI) to manage two main stations: a time-based liquid filling station and an automated capping station. Experimental results demonstrate significant performance enhancements across key metrics. In terms of volumetric dispensing precision, the centralized setup demonstrated substantial reproducibility, yielding a mean cycle duration of 5.003 s paired with a minimal temporal standard deviation of 0.018 s, thereby preserving a 100% operational accuracy metric. Regarding manufacturing capacity, the automated capping subsystem sustained an average throughput of 61.9 BPM, which nearly scales the baseline manual output (31.5 BPM) by a factor of two, while securing a 98% successful sealing rate. In conclusion, this study confirms that utilizing a unified PLC/HMI framework to integrate filling and capping stages significantly enhances both production speed and precision, providing a reliable and cost-effective automation solution for improving the operational efficiency of Small and Medium Enterprises in the beverage industry.

Keywords: Automated Control System, Programmable Logic Controller, Filling System, Capping System, Production Efficiency.

1. Introduction

Industrial automation serves is a fundamental element of Industry 4.0, driving improvements in production throughput, cost efficiency, and operational consistency. Central to this technological shift are Programmable Logic Controllers (PLCs), which are widely deployed in industrial automation frameworks owing to their deterministic execution, high reliability, and versatility in managing complex sequential logic (Bolton, 2015). To ensure optimal system performance, the selection of hardware such as the OMRON CP1L-EM is often based on the specific input/output requirements of the application (Thongphanh, 2020). Furthermore, the integration of PLC with Human–Machine Interface (HMI) systems, such as those from OMRON, significantly enhances real-time monitoring capabilities and operator interaction (Singh & Prakash, 2021).

Within beverage manufacturing processes, bottle filling and capping constitute critical steps that directly affect final product quality and safety standards. High precision is indispensable during these stages, as substandard capping poses risks of leakage and chemical/biological contamination, which ultimately degrades overall operational efficiency. To address these vulnerabilities, PLC-based monitoring and control systems have been successfully implemented in water purification and bottling plants to improve process accuracy and system stability (Arumugam & Shanmugasundaram, 2018; Pradhan & Mishra, 2020). Recent advancements have also expanded the scope of such systems to include remote monitoring via GSM and web servers, particularly for water level management and environmental data logging (Dinh & Tran, 2021; Parmanee, 2024).

In Lao PDR, research has increasingly focused on the effectiveness of PLC–HMI frameworks within local industries. Notably, Southisombath and Thongphanh (2025) reported that integrating PLC and HMI significantly improved monitoring reliability and operational transparency at the Xeno Drinking Water Factory. Their findings confirmed that centralized PLC control enhances system stability while reducing operational errors. This aligns with other regional studies which demonstrated that PLC–HMI integration markedly improves control accuracy in automated water systems (Nguyen & Pham, 2019). Additionally, efforts in designing energy-efficient control systems for rural water pumping and smart monitoring for local water usage further showcase the versatility of these technologies in the Lao context (Kittisak & Suksawat, 2022; Phimmasone & Inthavong, 2021).

For Small and Medium Enterprises (SMEs) in Southeast Asia, the adoption of automation is a vital driver for increasing production stability and regional competitiveness (Lao & Kim, 2021). Low-cost PLC and SCADA alternatives are considered highly suitable for small industries seeking to reduce labor dependency and minimize process variation (Lin & Li, 2020; Mishra et al., 2020). Furthermore, compliance with optimized HMI design methodologies plays a pivotal role in minimizing human errors while elevating overall system ergonomics and operability (Zhang & Wu, 2019).

Notwithstanding these macro-level advancements, domestic small-scale beverage enterprises within the Lao PDR still face difficulties in fulfilling market requirements due to severe operational bottlenecks. Empirical data gathered from local production lines demonstrates that a reliance on manual labor constrains the maximum output rate to a mean value of just 31.5 bottles per minute (BPM), which translates to roughly 1,890 bottles per hour. This restricted manual throughput proves insufficient for satisfying spiked consumer demands during high-season intervals, which strictly necessitate uninterrupted and high-rate manufacturing capabilities. Additionally, unautomated, open-loop interventions exacerbate process inconsistencies and fluid spillage, thereby generating substantial material losses and volatile product standards.

To address this technological disparity, deploying automated frameworks capable of stabilizing and scaling up manufacturing throughput has become an imperative necessity. Nonetheless, a review of existing literature reveals a scarcity of research dedicated to consolidating both filling and capping operations within a centralized, budget-friendly, single-PLC framework tailored to optimize end-to-end operational efficiency for domestic manufacturing plants. Therefore, this study proposes an integrated PLC/HMI-based automation system that combines time-based filling and sequential capping within a centralized framework. By transitioning from an inefficient manual setup to a high-precision automated production system, the proposed solution aims to nearly double the throughput to 61.9 BPM, maximize filling accuracy, and minimize process variation, ultimately providing a reliable and scalable automation model for SMEs in Lao PDR.

2. Materials and Methods

2.1 Experimental Configuration

The physical prototype developed for this research replicates the functional operations of an automated industrial beverage packaging system. The hardware architecture is centered around the OMRON CP1L-EM40DT-D programmable controller, which incorporates integrated Ethernet ports to facilitate uninterrupted communication and data exchange with the OMRON NS5-SQ11-V2 Human–Machine Interface (HMI).

The physical system is divided into two primary functional units (as shown in Figure 1 and Figure 2):

- Conveyor and Sensing Unit: A DC motor-driven conveyor belt facilitates bottle movement. Bottle detection is achieved using Photoelectric Sensors (E3F-DS30C4), which provide input signals to the PLC to trigger specific process stages.
- Filling and Capping Actuation Systems: To regulate fluid dispensing, the filling module incorporates a Solenoid Valve configured for precise, time-deterministic duration control. Concurrently, the capping module integrates a Pneumatic Cylinder coupled with a dedicated DC/stepper motor to execute the automated mechanical fastening of bottle closures.

2.2 Software Tools

To develop and manage the automation logic, two primary software suites were utilized:

- CX-Programmer (version 9.6): Used for developing the Ladder Diagram (LAD) logic, allowing for real-time debugging and monitoring of the sequential operations (Bolton, 2015).
- CX-Designer: Employed to create the graphical user interface for the NS5 HMI, enabling operators to set parameters such as filling time and to monitor the production count and system status in real-time (Zhang & Wu, 2019).

2.3 Control Logic Design

The operational sequence is governed by a sequential control architecture engineered to transition the manufacturing process from a manual open-loop regime into a fully automated, feedback-driven closed-loop system. The execution sequence adheres to the designated control algorithm (illustrated in Figure 3 and Figure 4):

1. System Initialization: Upon startup, the HMI establishes a deterministic data link with the PLC, enabling the operator to configure the desired filling time parameters.
2. Detection & Filling: As a bottle reaches the filling station, the photoelectric sensor sends a high signal to the PLC, which halts the conveyor and

activates the solenoid valve for the predefined duration ($t = 5$ seconds).

3. Capping Operation: Following the completion of the filling cycle, the conveyor system transports the container to the sealing zone. Subsequently, a secondary proximity sensor activates the pneumatic actuator to extend downward, exerting the required mechanical pressure to firmly fasten the closure (Singh & Prakash, 2021).
4. Feedback Loop: The HMI updates the total count of successfully processed bottles and displays any operational errors detected by the system sensors (as shown in Figure 5).

2.4 Experimental Procedure and Data Collection

To assess the operational efficacy of the proposed centralized framework, the empirical evaluation was structured into two distinct experimental phases:

- Volumetric Filling Precision Evaluation: The control logic was configured to execute a deterministic 5-second fluid dispensing cycle. Ten consecutive trials were performed, and the actual filling time was recorded using a high-precision digital chronometer to calculate the mean and standard deviation (SD), ensuring process consistency (Arumugam & Shanmugasundaram, 2018).
- Efficiency and Success Rate Test: The automated system was operated for 60 seconds to determine the number of bottles processed per minute (BPM). This was compared against manual labor performance data. Additionally, a batch of 50 bottles was processed to calculate the capping success rate, identifying any mechanical failures or timing misalignments (Pradhan & Mishra, 2020).

2.5 Data Analysis

The collected data were analyzed using descriptive statistics, including the arithmetic mean to evaluate average performance and standard deviation to assess process consistency. Furthermore, a relative gain equation was employed to mathematically quantify the throughput enhancements achieved by the automated setup over the baseline manual operations.

3. Results

The operational performance of the proposed centralized PLC architecture was validated through a series of empirical assessments focusing on fluid dispensing precision, mechanical sealing efficacy, and total manufacturing throughput. The following sections detail the experimental findings and provide a comparative analysis against existing manual operations.

3.1 Filling Precision and Consistency

The performance of the time-based filling station was evaluated to determine its ability to deliver consistent liquid volumes based on a preset duration of 5.000 seconds. To statistically validate the reliability of this framework, a sequence of ten experimental runs was executed, wherein the real-time duration of each actuation cycle was captured via a high-resolution digital chronometer.

To mathematically evaluate the operational stability of the fluid dispensing process, the arithmetic mean ($\bar{x}$) was computed to establish the baseline performance, while the standard deviation (SD) was leveraged as the primary metric for quantifying process volatility. The respective mathematical definitions for these statistical indicators are articulated in Equations (1) and (2):

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (1)$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \qquad (2)$$

In this context, the parameter x_i denotes the specific fluid dispensing duration logged during each experimental run, whereas n signifies the cumulative dataset size ($n = 10$). The compiled empirical data are consolidated in Table 1.

Based on the statistical evaluation, the system demonstrated a mean dispensing time of 5.003 seconds, maintaining an exceptionally narrow standard deviation of 0.018 seconds. This minimal variance indicates high repeatability and precision in the PLC's timing execution. Such consistency ensures that the liquid volume remains uniform across all processed bottles, representing a significant technical improvement over the inherent variability of manual estimation (Arumugam & Shanmugasundaram, 2018).

3.2 Capping Success Rate

To evaluate the operational dependability of the automated sealing mechanism, an experimental batch comprising 50 container units was processed. A "success" was defined as a cap being fully tightened without misalignment or damage. Out of the total sample size, 49 units were executed flawlessly, translating into a calculated process reliability rate of 98%. The single failure was attributed to a slight mechanical misalignment of the cap before entering the pneumatic press, suggesting a need for a more rigid cap-feeding mechanism in future iterations.

3.3 Comparative Efficiency Analysis

A primary objective of this research was to quantify the productivity gains achieved by transitioning from manual labor to an integrated PLC-based automation system. The throughput of both methods was measured in bottles per minute (BPM). To determine the efficiency increase, the percentage improvement was calculated using the following equation:

$$Improvement(\%) = \left(\frac{BPM_{automated} - BPM_{manual}}{BPM_{manual}}\right) \times 100\% \qquad (3)$$

Where $BPM_{automated}$ is the production rate of the proposed system and BPM_{manual} is the average rate achieved by a human operator. The comparative data is presented in Table 2.

Upon evaluating the empirical findings through Equation (3), the automated framework exhibited a manufacturing throughput of 61.9 BPM. This indicates a 96.5% performance enhancement relative to the baseline manual operation rate of 31.5 BPM.

To contrast the operational stability and throughput of both methods, a continuous 5-minute monitoring test was conducted, as illustrated in Figure 6. The timeline analysis demonstrates that while manual labor suffers from performance fluctuations due to operator fatigue and varying physical reaction times (ranging from 30 to 33 b/mn), the PLC-based automated system maintains a highly consistent and stabilized output at an average of 61.9 b/mn. This steady horizontal trend in the automated timeline reinforces the system's capability to safely eliminate human-induced bottlenecks and reliably satisfy high market consumption demands over extended operational periods.

To analyze these results within a practical framework, the traditional manual process delivers an actual production output of approximately 1,890 bottles per hour. Within the sector of domestic micro-industries, this constrained throughput routinely falls short of satisfying surged market requirements, inducing severe inventory deficits and operational constraints. Conversely, the proposed PLC-based automation system elevates the production capacity to 3,714 bottles per hour, effectively doubling the throughput within the same operational timeframe. By stabilizing the cycle times and achieving a 98% capping success rate, the automated framework successfully resolves human-error-induced delays and open-loop inefficiencies. Consequently, these findings validate that the integration of a unified PLC/HMI system successfully satisfies rising market demands, presenting a reliable, high-throughput, and scalable solution for local beverage SMEs (Lao & Kim, 2021).

3.4 HMI Functional Performance

During the experimental runs, the OMRON NS5 HMI successfully maintained real-time communication with the PLC. The interface provided accurate data visualization for:

1. Production Counter: Correctly incremented for every bottle passing the final sensor.
2. Status Monitoring: Displayed real-time status of the solenoid valve and pneumatic cylinder.
3. Parameter Adjustment: Allowed for instantaneous changes to filling time without halting the entire system.

The functional test confirmed a 100% success rate in logic execution and HMI-PLC synchronization, verifying the reliability of the centralized control architecture.

4. Discussion

The derived laboratory data substantiate that the unified PLC-governed automation framework yields a profound advancement over manual techniques regarding both process repeatability and hourly throughput. This section analyzes the implications of these findings for the bottling industry and small-scale manufacturing.

4.1 Analysis of Filling Precision and Stability

The high consistency observed in the filling process, with a mean of 5.003 s and a standard deviation of only 0.018 s, underscores the superiority of deterministic PLC timing over manual human estimation. Under manual processing regimes, fluid dispensation depths frequently exhibit non-uniformity due to physical exhaustion of the operator and structural fluctuations in human reaction latencies, inevitably inducing material wastage or deviation from specified volumetric thresholds. The operational stability established in this investigation corroborates the assertions of Arumugam and Shanmugasundaram (2018), who highlighted that deploying automated, time-governed control sequences mitigates system variance. Securing such a high degree of process reproducibility remains imperative for small-to-medium enterprises seeking to preserve strict quality control and foster long-term customer reliability.

4.2 Throughput and Economic Impact

The most striking result is the production speed of 61.9 bottles per minute, which represents a 96.5% increase compared to the manual rate of 31.5 BPM. By approximately duplicating the manufacturing throughput, the automated framework enables enterprises to satisfy escalated market requirements without incurring a proportional surge in personnel expenditures. This finding supports the argument by Lao and Kim (2021) that automation adoption is a primary driver for competitiveness in Southeast Asian SMEs. The transition to an integrated PLC/HMI framework not only speeds up the cycle time but also reduces the physical strain on workers, potentially lowering long-term operational risks.

4.3 Integrated System Architecture and Scalability

Unlike traditional bottling lines that may use separate control units for different stages, this study utilized a single-PLC framework (OMRON CP1L-EM) to manage both filling and capping. Such a centralized configuration mitigates hardware redundancy, curtails inter-station data propagation delays, and diminishes cumulative capital expenditures (Mishra et al., 2020). The use of the NS5 HMI proved essential for operational transparency, allowing for real-time monitoring and parameter adjustments as advocated (Singh and Prakash, 2021).

However, the 98% success rate in capping indicates that while the electronic control logic is robust, the mechanical interface remains a point of potential failure. The 2% failure rate observed was likely due to the passive nature of the cap-feeding mechanism. As noted in recent studies on smart monitoring (Kittisak & Suksawat, 2022), the integration of more advanced sensors or a vision-based inspection system could potentially bring the success rate to 100% by detecting misaligned caps before the capping action occurs.

4.4 Implications for Local Industry in Lao PDR

The success of this prototype at the local level confirms the findings of Southisombath and Thongphanh (2025) regarding the reliability of PLC systems in the Lao industrial context. For local water factories, such as those in Xeno or other provinces, this integrated system provides a cost-effective blueprint for upgrading from manual to semi-automated or fully automated production. The proposed framework strikes an optimal equilibrium between advanced technological functionalities and the financial limitations characteristically encountered by localized small-to-medium enterprises.

5. Conclusion

This investigation demonstrates the successful design, assembly, and implementation of this automated system for container dispensation and sealing processes, managed via a centralized PLC/HMI topology. The gathered empirical data confirm that migrating from conventional, open-loop human-dependent workflows to an integrated, centralized control architecture substantially elevates manufacturing throughput, volumetric precision, and long-term operational dependability. With an average filling time of 5.003 seconds and an exceptionally low standard deviation of time at 0.018 seconds, the system guarantees precise liquid level uniformity. Additionally, the automated production rate of 61.9 bottles per minute (BPM)—representing a 96.5% increase over manual labor (31.5 BPM)—confirms the framework's capability to substantially expand manufacturing capacity.

By integrating the OMRON PLC and HMI system, local beverage manufacturers can effectively forecast and scale their daily operations. Extrapolated across a standard 8-hour operational shift, the automated deployment facilitates a projected daily throughput of 29,712 units, whereas the conventional human-driven alternative yields merely 15,120 units. This predictable and elevated output directly resolves market supply shortages during peak demand periods. Additionally, deploying this technological infrastructure strategically rationalizes workforce allocation by transitioning personnel from monotonous, high-fatigue activities to elevated supervisory responsibilities, thereby mitigating human-error-related disruptions and occupational hazards. Financially, minimizing liquid spillage and stabilizing the capping success rate at 98% leads to significant material cost savings and minimized product rejection rates.

In summary, the proposed unified architecture establishes a reliable and efficient automated system that is also cost-effective. It serves as a practical technological pathway for Small and Medium Enterprises (SMEs) in Lao PDR to transition toward Industry 4.0 standards, eliminate heavy labor dependency, reduce structural overhead costs, and maintain a highly competitive production quality in the regional market.

6. Conflict of Interest

The authors affirm that no competing financial or personal interests exist that could influence the objectivity of the work presented in this paper. This investigation was performed in strict alignment with academic ethics, and the compiled empirical outcomes are entirely free from any commercial or non-academic pressures from equipment suppliers or external entities.

7. Acknowledgments

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Table 1. Experimental Results of Filling Time Consistency (Target = 5.000 s)

Trial No.	Actual Filling Time (s)	Deviation (s)
1	5.02	+0.02
2	4.98	-0.02
3	5.01	+0.01
4	5.00	0.00
5	5.03	+0.03
6	4.97	-0.03
7	5	0
8	5.01	+0.01
9	4.99	-0.01
10	5.02	+0.02
Mean ($\bar{x}$)	**5.003**	**+0.003**
Std. Dev (SD)	**0.018**	**-**

Table 2. Throughput Comparison: Manual vs. Automated System

Metric	Manual Labor	Automated System	Improvement (%)
Bottles Per Minute (BPM)	31.5	61.9	+96.5%
Process Stability	Low	High	N/A
Labor Dependency	High	Low	N/A

Figure 1. The integrated automated bottling system setup including PLC, HMI, and conveyor unit.

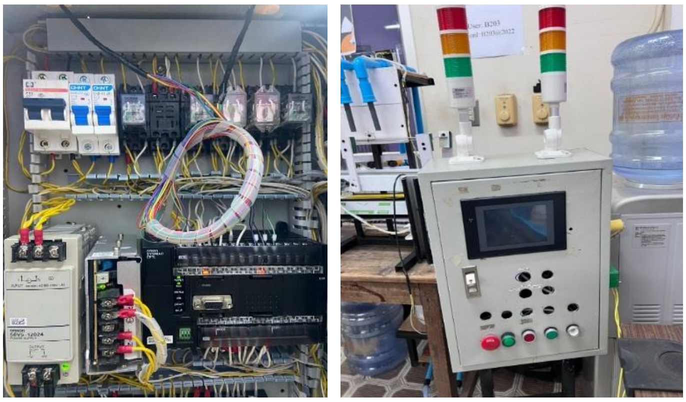

Figure 2. Hardware connection diagram between Omron CP1L PLC and NS5 HMI.

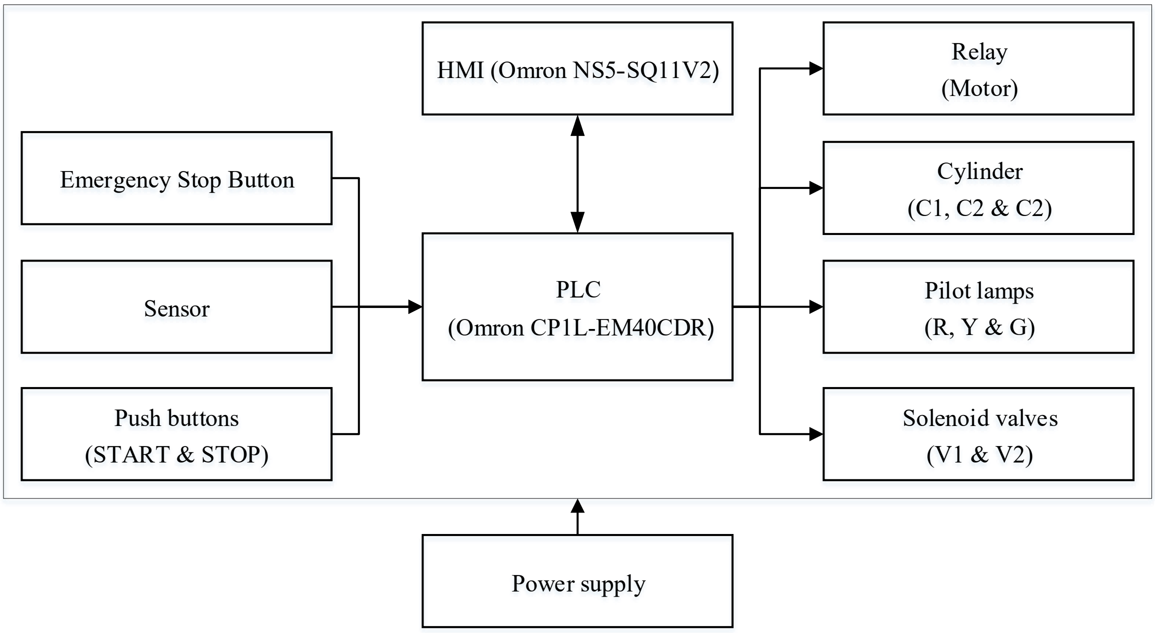

Figure 3. Flowchart of the sequential logic for filling and capping processes.

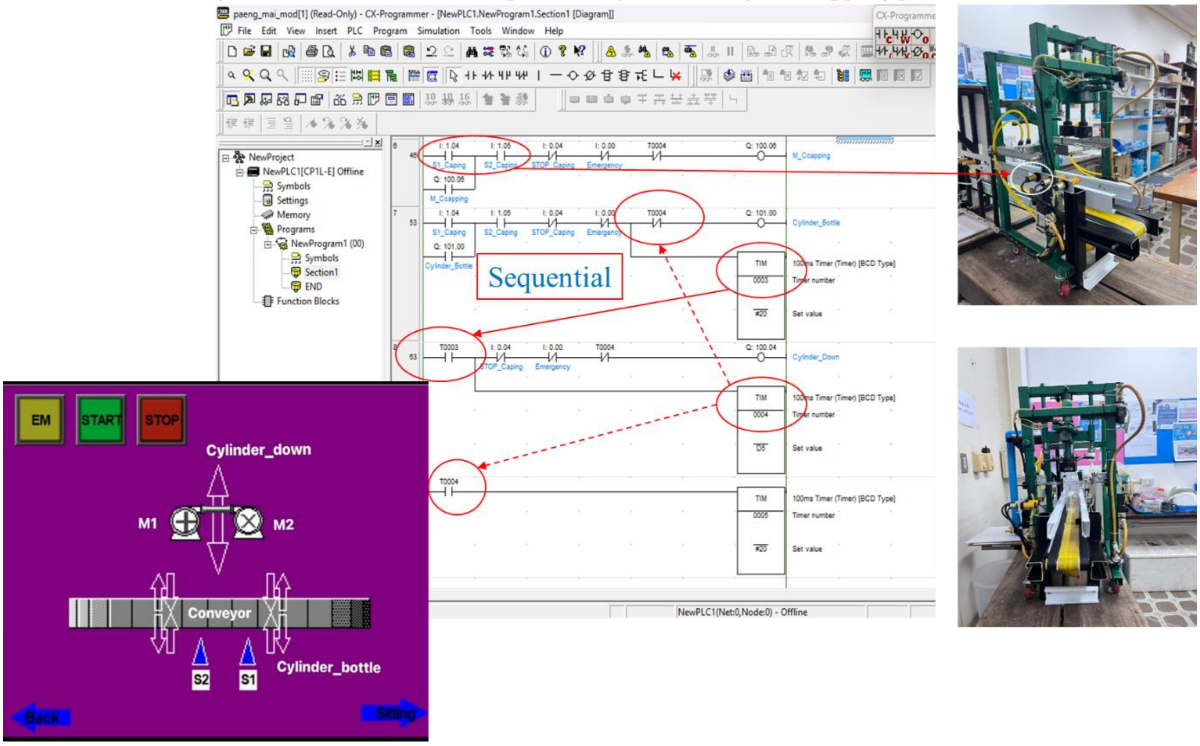

Figure 4. PLC ladder logic for time-based filling and pneumatic capping control.

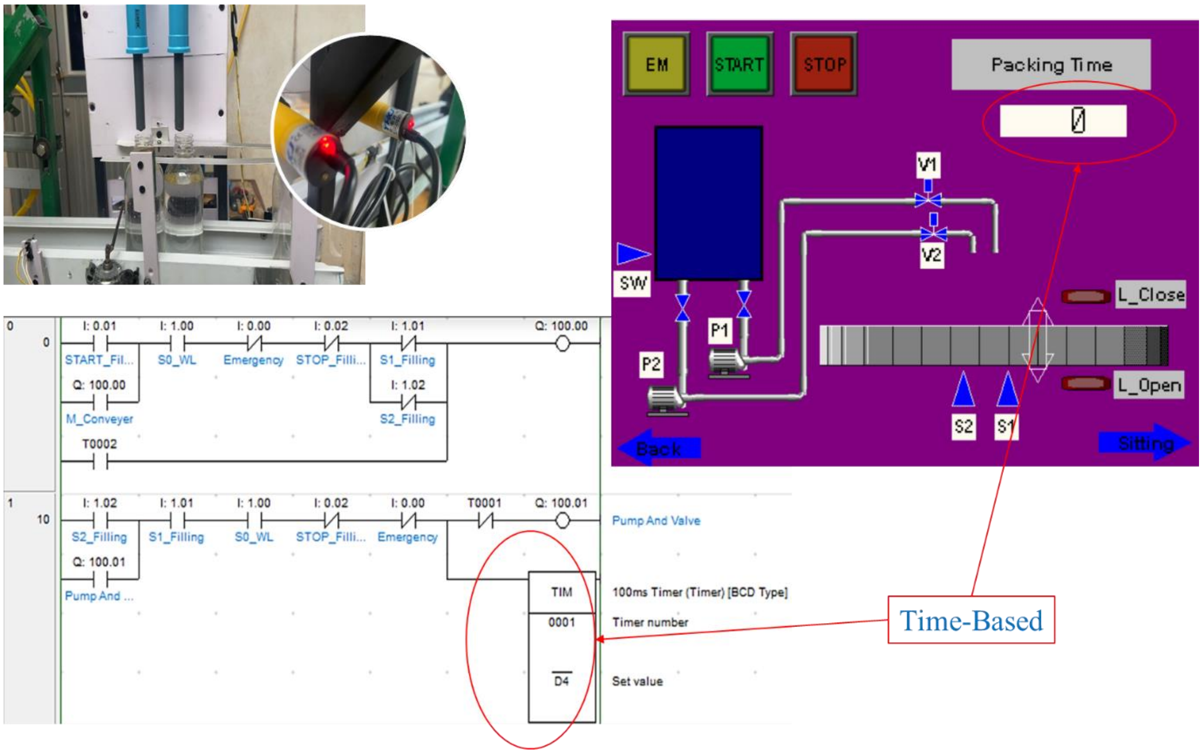

Figure 5. HMI dashboard displaying real-time production monitoring and parameter settings.

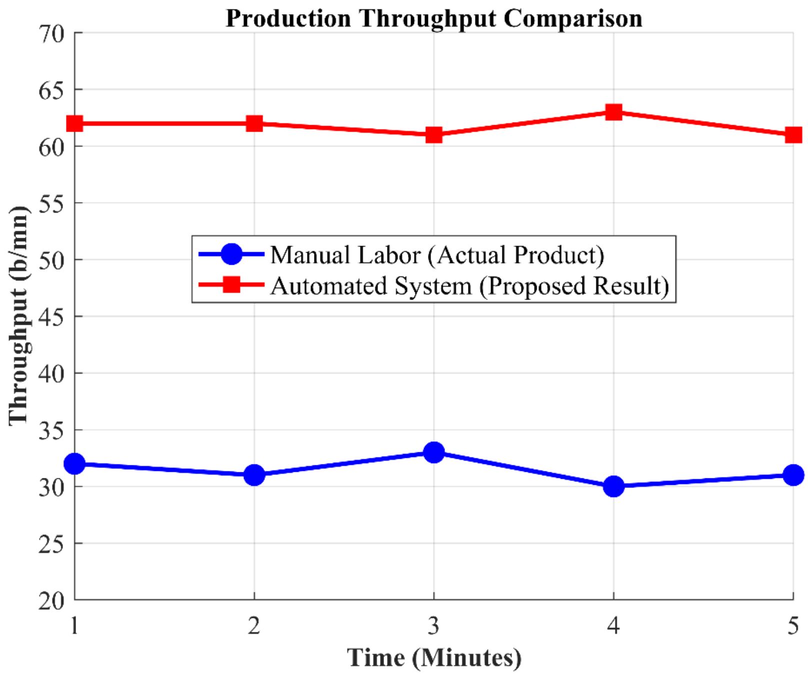

Figure 6. Comparative analysis of manufacturing throughput (units per minute) evaluating the conventional manual process (blue trace) against the integrated PLC-governed framework (red trace) across a 5-minute continuous observation window.