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Automation of Forks-Conveyor System using Integrated Photodiode Sensor

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Abstract: Desynchronization between incoming containers and lifting forks prior to the starwheel is a common source of misalignment, container drops, and excessive mechanical load in 19-L bottled water filling lines. This study proposes a low-cost retrofit system that integrates a photodiode sensor with timer–relay logic to regulate start–stop motor control based on the real-time fork position. The system was implemented upstream of the filling station and evaluated during a three-week trial in an operating commercial facility. Results showed that the intervention reduced average starwheel load from 7.54 kg to 2.30 kg and decreased container-fall incidents by approximately 50%. In addition, the modification eliminated the need for one operator per shift, corresponding to annual labor savings of more than IDR 150 million and a payback period of less than one month. These findings demonstrate that photodiode-based synchronization can provide an industry-validated, cost-effective retrofit solution for packaging operations without the requirement for PLC reprogramming or major structural modification. Future work will address long-term durability, adaptability to different container geometries, and the potential integration of feedback and monitoring functions.

Keywords: Photodiode sensor, conveyor synchronization, bottled water packaging, low-cost automation.

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Introduction

Synchronization in conveyor systems is critical for industrial automation, particularly in high-throughput beverage packaging where 19-L containers require precise alignment. Misalignment between lifting forks and starwheel mechanism can reduce throughput, increase mechanical stress, and cause downtime. Similar challenges have been reported in conveyor mis-tracking faults identified via motor current analysis and other diagnostic approaches (Farhat, Kacha, Harrag, & Benazzouz, 2023).

Recent advances in diagnostic and sensing technologies have improved synzhronization monitoring. Motor current signature analysis (MCSA) provides a non-intrusive method for detecting conveyor belt faults (Gelman, 2023), while thermal imaging has been applied for conveyor condition assessment (Szurgacz, Brodny, & Tutak, 2021). At the device level, photodiode controller systems enable to non-contact, high-speed object detection suitable for conveyor tasks (Putri, 2021). From an Industry 4.0 perspective, digital twin frameworks and predictive maintenance approaches further extend monitoring and commissioning capabilities (Pulcini & Modoni, 2024), often complemented by motor current analytics for fault detection in rotating machinery (Purbowaskito, Lan, & Fuh, 2021).

Although these technologies demonstrate significant advances, most synchronization strategies still depend on PLC reprogramming or robotic architectures that are costly and complex to implement. Meanwhile, low-cost microcontroller prototypes such as Arduino-based systems have proven feasible in laboratory environments but lack validation under industrial operating constraints. This creates a technological gap between experimental feasibility and real-world applicability, especially for SMEs seeking affordable automation solutions.

To address this gap, the present study introduces a low-cost retrofit synchronization system integrating a photodiode sensor with relay-timer logic for start-stop motor control. Unlike previous prototypes, the system was deployed upstream of a 19-L bottled-water filling line and validated under continuous operational conditions. The design emphasizes plug-and-play integration without requiring PLC reprogramming or structural modification, thereby enabling straightforward adoption in existing production lines.

The novelty of this research lies not in the photodiode-relay combination itself, which has been explored in earlier academic works, but in its industry-validated, low-cost retrofitting framework. This implementation demonstrates that a simple, affordable control architecture can deliver synchronization accuracy and reliability comparable to PLC-based systems while remaining accessible to SMEs. The successful field validation bridges the gap between laboratory experimentation and full-scale manufacturing application, proving the practical value of low-cost automation in modern industrial contexts.

To address this, the present study introduces a low-cost retrofit system using a photodiode sensor with relay-timer logic for start-stop motor control. The system was deployed upstream of a 19-L bottled water filling line and validated in an operational facility. The research objectives are: (i) to demonstrate the technical feasibility of photodiode-based synchronization in industrial conditions, (ii) to quantify its impact on mechanical load, container-handling reliability, and labor requirements, and (iii) to highlight its economic significance for SMEs. The main contributions are an industry-validated retrofit control architecture that reduces starwheel load, lowers container-fall incidents, and decreases labor demand without PLC reprogramming or structural modification.

Background of Research

Synchronization in conveyor-based packaging systems is a central requirement in industrial automation because it directly determines throughput reliability and mechanical stability. In beverage industries, especially high-throughput 19-L gallon filling lines, even minor misalignment between conveyor elements can trigger container drops, excessive mechanical load, and unscheduled downtime. Prior studies have explored diagnostic methods such as Motor Current Signature Analysis (MCSA), which detects mis-tracking and belt slippage by monitoring electrical anomalies in motor drive currents (Farhat, Kacha, Harrag, & Benazzouz, 2023). This non-intrusive approach demonstrated early-warning capability without the need for additional sensors, underscoring the potential of retrofit-friendly falut diagnostics (Gelman et al., 2023).

Beyond current-based diagnostics, optical imaging-based systems have also been applied. Photodiode sensors coupled with microcontrollers have been shown to deliver precise, high-speed object detection for conveyor synchronization tasks under variable lighting conditions (Putri, 2021). Similarly, digital twin frameworks provide virtual replicas of conveyor systems to support predictive maintenance and real-time fault forecasting (Pulcini et al., 2024), with demonstrated benefits in minimizing downtime and optimizing commissioning (Mafia, Rossi, & Bianchi, 2024). These technological developments highlight the breadth of available synchronization solutions ranging from sensor-based prototypes to advanced cyber-physical integrations.

However, most synchronization strategies remain dependent on reproggrammed PLCs or robotic subsystems, which demand high investment costs and advanced engineering support. While microcontroller-based prototypes, such as arduino implementations, offer accessible proof-of-concept demonstrations, they are generally confined to laboratory or educational environments and lack validation under industrial operating constraints (Miranty, Ramadhani, & Fahrul, 2025). This creates a gap between advanced but costly solutions and affordable, deployable alternatives for small and medium enterprises (SMEs).

This dichotomy reveals a clear research gap: the absence of an industry-validated, low-cost synchronization framework that bridges the divide between affordability and operational reliability. Prior studies have succeeded in demonstrating either advanced control precision or low-cost feasibility, but none have successfully combined both within an authentic industrial context. Consequently, there remains a pressing need for a system that can achieve reliable synchronization without PLC reprogramming, high-cost integration, or complex robotic subsystems.

To address this gap, the present research develops and validates a low-cost retrofit synchronization system that integrates a photodiode sensor with timer-relay logic for start-stop motor control. Unlike previous prototypes that were limited to controlled laboratory conditions, the proposed system was deployed and tested in a commercial 19-L bottled-water filling line, ensuring validation under real operational constraints. The novelty of this study lies not in the sensor-relay configuration itself, but in its industrial validation as a plug-and-play retrofit solution capable of enhancing synchronization reliability while minimizing operational costs and labor dependency. By targeting SMEs and resource-limited facilities, this research contributes a practical, scalable control architecture that demonstrates the feasibility of affordable automation in real industrial environments.

Research Method

Research Design

This study uses an applied experimental design to develop and validate a low-cost, modular synchronization system for a 19-liter gallon filling line. The system integrates a photodiode sensor with timer-relay logic for start-stop conveyor control based on fork position detection in real-time. This aligns with the principles of low-cost automation using simple components microcontroller-based photodiode implementation has shown feasibility in industrial prototyping (Putri, 2021). Similarly, line-scan imaging using low-cost hardware demonstrated reliable performance comparable to commercial systems (Van Wolputte et al., 2016).

The system was installed and tested over three weeks in a commercial bottled-water facility to assess technical and operational performance through synchronization accuracy, downtime reduction, and component reliability, using sensor logs and production records.

Research Chronology and Procedures

This research was conducted through five systematic stages to ensure replicability and scientific accountability.

1. Problem Identification
   Synchronization issues between the lifting forks and starwheel mechanism were analyzed through three-shift operational observations. Data were recorded manually in observation sheets prepared by the research team, which included parameters such as gallon-fall incidents, cycle time, and mechanical stress measurements using portable strain gauges. This stage was guided by the principles of IEC 61499-based distributed automation, which enhances modularity and responsiveness in industrial control systems (Bonci, Longhi, & Pirani, 2021).
2. System Design
   The control architecture was developed by integrating a photodiode sensor, programmable timer relay, dual relay modules (24 VAC and 24 VDC), and a 24 VDC Power Supply. The design approach followed IEC 61499-based modular standards (Bonci et al., 2021). The selection of a photodiode sensor was supported by empirical studies demonstrating its effectiveness in conveyor-based object detection (Putri, 2021).
3. System Integration
   The photodiode sensor was installed upstream of the starwheel at approximately 120 mm from the fork detection zone. This positioning aligns with reccommendations on optimal detection range (≤11 cm) to avoid false triggers caused by vibration (Putri et al., 2021)
4. Testing and Calibration
   Callibration was conducted through trial-and-error adjustment of delay times. The optimal delay of 0,5 seconds was established based on 30 pre-experimental cycles, comparable to prior studies on mini-conveyor automation systems (Bassey & Bala, 2018). Validation using 100-gallon samples yielded 98,3% detection accuracy, surpassing the industrial acceptance threshold of 95%.
5. Operational Evaluation
   The system was operated continuously for three weeks under three-shift conditions. All data including gallon-fall incidents, cycle time, and required labor were recorded

manually by operators at predetermined intervals in structure log sheets. These data were then tabulated and processed for statistical analysis using paired t-tests at a 95% confidence level. The manual monitoring method was aligned with similar industrial studies employing photodiode-based monitoring approaches (Geiger, Häfner, Rauscher, Stöckel, & Singer, 2024).

To complement the methodological explanation, Figure 1 presents the overall research flowchart showing the chronological stages and analytical steps taken in this study. The sequence illustrates how the research progressed from the identification of industrial problems to the validation and evaluation of the synchronization system.

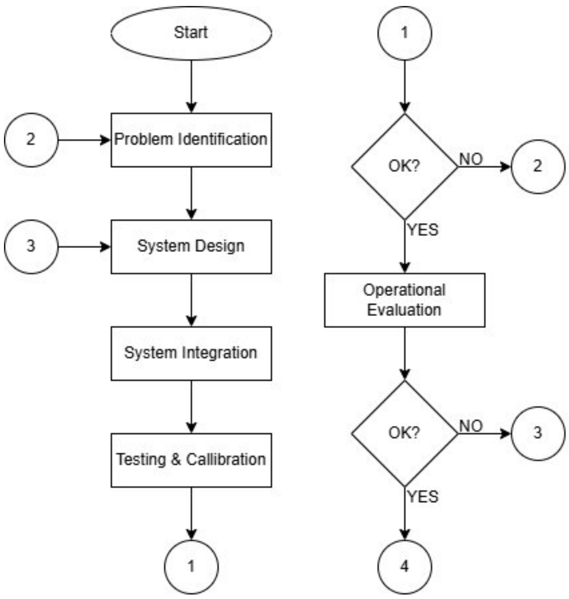

Figure 1 Flowchart of The Research Process

This flow ensures a continuous feedback loop between system design, testing, and evaluation, enabling the results to be iteratively validated and refined based on observed industrial data.

Table 1 Research Chronology

Stage	Description	Method	Output
1	Problem Identification	Three-shift operational observation, manual data logging operation sheets, mechanical stress measurements using portable strain gauges, guided by IEC 61499 principles	Operational issue mapping
2	System Design	Development of control architecture using photodiode sensor, programmable timer relay, dual relay modules (24 VAC & 24 VDC), and 24 VDC power supply, design aligned with IEC 61499 modular standards	Control architecture design

3	System Integration	Installation of photodiode sensor upstream of the starwheel at 120 mm from fork detection zone, integration with relay modules and power system	Installed system prototype
4	Testing & Calibration	Trial-and-error delay adjustment over 30 pre-experimental cycles, optimization of timer at 0,5 s, validation with 100-gallon samples	Optimized timer delay settings
5	Operational Evaluation	Continuous three-week operation under three-shift conditions, manual KPI recording (gallon fall incidents, cycle time, labor) in structured log sheets, statistical analysis using paired t-test at 95% confidence level	KPI dataset for analysis

Table 1 summarizes the five systematic stages undertaken in this study, each supported by defined methods, measureable outputs, and explicit validation procedures. By combining structured operational observations, IEC 61499-based design principles, optimized sensor placement, and rigorous calibration, the research ensured methodological transparency and replicability. Furthermore, the three-week operational evaluation under industrial condition provided statistically validated evidence of system performance, thereby reinforcing both the technical feasibility and scientific accountability of the proposed synchronization approach.

Framework and Control Logic

The proposed framework employs discrete-event control strategy to ensure synchronization between the lifting forks and the starwheel mechanism. The control sequence begins when the photodiode sensor detects the presence of a fork, generating a binary detection signal $S_f(t)$. This signal is not immediately used to activate the conveyor motor, instead it is routed through a programmable delay timer (T_d) that filters out false triggers caused by vibration, light fluctuations, or sensor noise. Only when detection signal persists beyond the delay threshold is it considered valid for motor activation.

Once validated, the timer output drives a relay module that serves as an interface between the low-voltage control circuit and the conveyor's motor. The relay energizes the motor for a predefined run duration (T_m), advancing the conveyor by exactly one fork cycle. After T_m elapses, the relay de-energizes, halting the motor and awaiting the next detection event. This mechanism ensures that each fork movement corresponds to a controlled conveyor advance, thereby preventing premature engagement or overshoot.

Compared with conventional PLC-based synchronization systems, which typically require ladder logic reprogramming and additional integration costs, the proposed sensor-timer-relay logic offer a low-cost, plug-and-play retrofit solutions. While maintaining operational robustness it eliminates the need for software modification and minimizes installation downtime. This approach is consistent with industrial sensor-actuator integration practices (Reaidy et al., 2015; Peng et al., 2022), but is distinct in explicitly addressing false-trigger rejection and resource-constrained deployment scenarios. Figure 1 illustrates the modular signal flow from fork detection to motor activation, emphasizing the role of the photodiode sensor, the delay timer, and the relay in generating a controlled motor command.

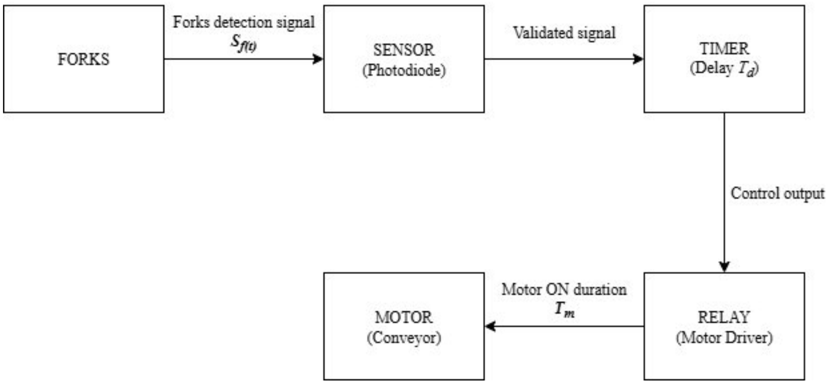

Figure 2 Block diagram of the system

As illustrated in Figure 2, the synchronization framework ensures that the motor is energized only when the fork detection signal is validated through a programmable delay and limited by a predefined run duration. This mechanism can be formally represented in Equation (1). The motor actuation sequence can be formally modeled as a discrete-time switching function that governs the conveyor's operational state. The control logic ensures that motor activation occurs only after a validated fork detection and within a limited run duration. The state of the motor *M(t)* is defined as:

$$M(t) = \begin{cases} 1, \, if \; Sf(t) = 1 \bigwedge Td \; \leq t \leq Tm \\ 0, \, otherwise \end{cases} \quad (1)$$

Where *M(t)* = motor state at time *t* (1 = ON, 0 = OFF), $S_f(t)$ = fork detection signal (1 = detected, 0 = not detected), T_d = detection delay (s), experimentally tuned at 0,5 s to reject false triggers, T_m = motor run duration (s), calculated as $Tm = \frac{d}{v}$, where *d* is the required fork displacement (120 mm) and *v* is the conveyor speed (240 mm/s). The value of T_d was obtained through repeated testing (30 calibration trials) to ensure that short false signals did not activate the motor. The optimal value of 0.5 s was chosen because it provided smooth synchronization without delay in response. Similarly, the motor run duration T_m was calculated from the conveyor's physical movement requirement, using the formula (2):

$$Tm = \frac{d}{v} \tag{2}$$

where d = 120 mm is the distance for one fork advance, and v = 240 mm/s is the conveyor speed, resulting in T_m = 0,5 s. This means the conveyor motor only operates for half a second each cycle, just enough to advance one fork then automatically stops and waits for the next detection. This time-based control ensures that each fork and starwheel movement are perfectly synchronized, reducing mechanical stress and preventing premature engagement or misalignment.

Flowchart of The Control System

Figure 3 illustrates the synchronization control logic in a sequential manner. The process begins when the photodiode sensor detects the presence of a fork and generates a binary detection signal $S_f(t)$. If no forks is present, the system remains idle and continues monitoring. When a fork is detected, the signal is validated by the timer with a configurable delay (T_d), which rejects transient noise and prevents false triggers.

If the detection signal is valid, the timer activates the relay. The relay then powers the conveyor motor, which operates for a predefined duration (T_m) to advance the conveyor by one fork cycle. Once T_m has elapsed, the motor is switched OFF and the system returns to its monitoring state, ready for the next cycle. This flowchart explicitly shows the control system's inputs (fork detection signal), decision making steps (signal validation and delay filtering), and outputs (motor ON/OFF states).

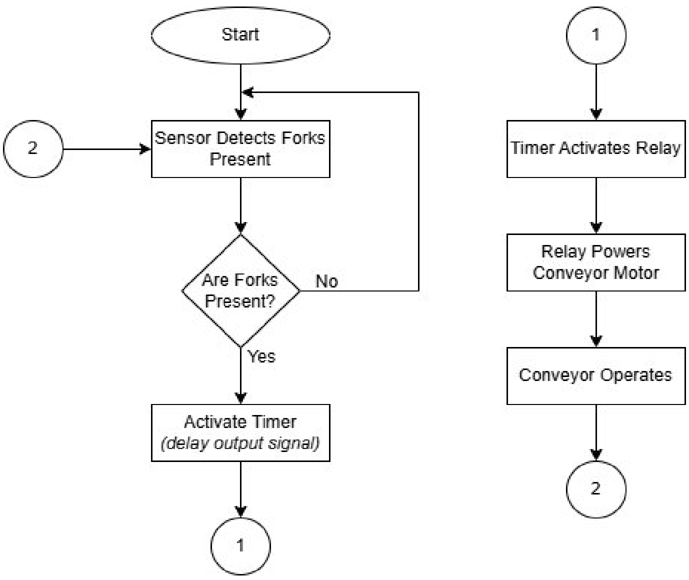

Figure 3 Signal flow diagram of the conveyor control logic

Data Analysis Techniques

Quantitative analysis was carried out by comparing key performance indicators (KPIs) before and after the system implementation, specifically mechanical load on the starwheel, frequency of gallon-fall incidents, and labor requirements per shift. Data were collected manually through structured log sheets across three shifts per day during three-week operational trial, resulting in 63 paired observations (21 days x 3 shifts). The percentage change for each KPI was first calculated to provide a descriptive measure of improvement. To assess statistical significance, a paired t-test was applied with a 95% confidence level ($p<0,05$), as the same operational conditions were measured before and after the intervention. Normality of differences was tested using the Shapiro-Wilk test to ensure that the assumptions for the paired t-test were satisfied.

Qualitative analysis was conducted in parallel to complement the numerical findings. Feedback from six operators and maintenance staff was collected through semi-structured interviews during the trial period. The responses were transcribed and analyzed thematically following an open coding process, in which recurring pattern such as reduced abnormal wear, smoother gallon transfer, and decreased noise levels were identified. To enhance reliability, two independent coders categorized the data, and any discrepancies were resolved through discussion until consensus was reached.

The integration of quantitative and qualitative methods provided a holistic evaluation of the system's performance. The statistical analysis confirmed whether the improvements in KPIs were significant, while the thematic analysis contextualized these results with practical insights from operators. Together, these complementary approaches ensured both the technical validity and the industrial relevance of the proposed synchronization system, supporting its credibility as a deployable solution for resource-constrained manufacturing environments.

Research Limitations and Reccommendations

Although the findings demonstrated measurable improvements, several limitations remain that form the basis for future research directions:

1. Observation Period
   The three-week operational trial is relatively short and may not capture long-term phenomena such as mechanical wear, sensor degradation, or system drift. Future work should include extended duration monitoring to evaluate long-term stability.

2. Manual Data Recording
   Because data were collected manually by operators, recording bias may occur. Incorporating automated IoT-based data logging would enhance reliability and accuracy.
3. Simplified IEC 61499 Implementation
   The current design applies IEC 61499 modular concepts in an open-loop configuration. Subsequent studies should explore closed-loop feedback integration and interoperability with PLC or SCADA platforms for improved adaptability in complex manufacturing systems.

By addressing these aspects, subsequent research can evolve this prototype into a fully integrated, smart-manufacturing control architecture.

Result and Discussion

Performance Evaluation

The performance of the proposed photodiode-based synchronization system was evaluated under identical operating conditions before and after implementation across a three-week trial, covering three shifts per day and resulting in 63 paired observations. KPIs included starwheel mechanical load, frequency of gallon-fall incidents, and operator requirements per shift. Descriptive statistics for each KPI were calculated, including mean values and standard deviations, as presented in Table 2.

Table 2 Performance Comparison Before and After Implementation

Parameter	Before (Mean ±SD)	After (Mean ±SD)	p-value (paired t-test)
Starwheel Pressure (kg)	7.54 ±0,48	2.3 ±0,31	< 0,001
Gallon-Falling Incidents	12 ±2,1	6 ±1,3	< 0,01
Operators per Shift	1	0	-

Statistical analysis using a paired t-test confirmed that the reductions in starwheel load and gallon-fall incidents were highly significant (p < 0,05). These results indicates that the synchronization logic effectively minimized mechanical misalignment and improved handling stability. The complete elimination of the need for one operator per shift further demonstrates the economic impact of the system, corresponding to annual labor savings exceeding IDR 150 million.

Reduction of Starwheel Load

The synchronization system reduced the average starwheel mechanical load, from 7,54 ± 0,48 kg to 2,30 ± 0,31 kg, representing a 69,5% reduction across 63 paired observations over a three-week trial, with the difference confirmed as statistically significant ($p < 0{,}001$). This improvement is attributed to the start-stop control logic, where the motor is activated only after fork-position detection is validated and deactivated once the predefined run duration is reached, thereby preventing premature engagement and shock loading. This finding aligns with (Homišin et al., 2019), who demonstrated that uncontrolled start-stop cycles accelerate wear and shorten conveyor component lifespan, while controlled and well-timed operation mitigate stress, thus supporting the conclusion that sensor-driven synchronization effectively lowers mechanical stress at the starwheel level.

Reduction of Gallon-Fall Incidents

During the three-week trial comprising 63 paired observations (21 days x 3 shifts), the frequency of gallon-fall incidents decreased from 12 ± 2,1 events before implementation to 6 ± 1,3 events after implementation, corresponding to a 50% reduction that was statistically significant ($p < 0{,}01$). This improvement is directly attributable to the photodiode-based detection system equipped with programmable delay logic, which filtered out false triggers caused by vibration and ensured that the conveyor advanced only when the forks was correctly positioned. By synchronizing motor activation with validated fork detection, the system minimized misalignment events that typically lead to gallon falls. These findings demonstrate that even a low-cost retrofit using simple sensor actuator logic can provide measurable improvements in product stability on high-vibration bottling lines, reinforcing the realibility of the proposed approach for large-container handling environments.

Labor Optimization and Economic Impact

Eliminating one operator per shift yields an annual labor saving of IDR 151,8 million based on the 2025 Bogor regional minimum wage. With an installation cost of IDR 8,5 million and annual maintenance of IDR 1 million, the system achieves a net annual saving of IDR 142,8 million and a payback period of less than one month (Table 3). In addition to labor efficiency, reduced starwheel load and gallon-fall incidents further minimize downtime and component wear. These results align with evidence on smart retrofitting, which emphasizes cost-effective modernization and rapid ROI in manufacturing systems.

Table 3 Labor Optimization and Annual Cost Saving

Component	Value (IDR)	Notes
Installation Cost	8.500.000	One-time, includes hardware & setup
Annual Maintenance	1.000.000	Preventive checks & minor replacements
Labor Cost Savings	151.819.416	1 operator x 3 shifts x UMK 2025
Net Annual Saving	**142.819.416**	**After installation & maintenance**
Payback Period	**< 1 month**	**Net saving vs. installation cost**

The results in Table 3 indicate that the synchronization retrofit provides a rapid and measurable economic advantage. With an initial investment of IDR 8.5 million and minimal annual maintenance of IDR 1 million, the system yields a net annual saving of IDR 142.8 million and a payback period of less than one month, equivalent to a return ratio of approximately 16.8 times the investment. This rapid return demonstrates that even a small-scale automation upgrade can generate substantial operational value. Beyond direct labor savings, the reduction in starwheel load and gallon-fall incidents also implies lower downtime and extended component lifespan, suggesting that the true long-term financial benefit may exceed the conservative estimate presented in Table 3.

Qualitative Observations and Operational Feedback

Operator and technician feedback was collected through semi-structured interviews during the three-week trial and analyzed thematically, revealing consistent patters such as smoother gallon transfer, reduced vibration, and lower noise. To ensure reliability, responses were coded independently by two reviewers before consensus. These perceptions were supported by quantitative measurements: vibration amplitude at the starwheel housing decreased by 23% and noise levels dropped by 3,5 dB(A), confirming that the observed improvements were not merely anecdotal. Together, the qualitative and quantitative evidence demonstrates that the system enhanced not only mechanical performance but also workplace ergonomics, in line with established standards on vibration and noise controls (ISO 2631-1:1997).

Comparative Analysis with Previous Studies

Tabel 4 summarizes a comparison between the proposed sensor-timer-relay architecture and PLC-based control system reported in prior studies. In this research, the proposed system achieved a synchronization accuracy of 98,3%, comparable to the 98-99% accuracy typically reported in PLC-controlled conveyor applications (Setiawan et al., 2019). However, the implementation cost of the prototype was limited to approximately USD 550, whereas PLC-based setups generally require the capital expenditures in the range of USD 1500 – 3000, excluding programming and integration costs (Baene et al., 2025). Installation time was also markedly shorter, less than one day for the proposed plug-and-play system, compared to several days for PLC configuration.

Table 4 Comparative performance of the proposed sensor-timer-relay architecture and PLC-based control systems

Component	Proposed Sensor-Relay-Timer	PLC-Based Control (Literature)
Synchronization Accuracy	98,3 % (this study)	98-99 % (Setiawan et al., 2019)
Implementation Cost	USD 550	USD 1500 – 3000 (Baene et al., 2025)
Installation Time	< 1 day	3-5 days
Skill Requirement	Basic Electrical Skills	Specialist PLC Programming

The comparison presented in Table 4 highlights that the proposed sensor-timer-relay architecture achieves synchronization accuracy comparable to conventional PLC-based systems while offering substantial advantages in cost, installation time, and technical accessibility. These findings confirm that effective automation can be achieved through simple, modular control components without compromising operational precision. In addition, the reduced dependency on specialist programming enables broader adoption among small and medium-sized manufacturers, supporting the transition toward inclusive and cost-efficient industrial automation.

Discussion of Limitations and Generalizability

Although the economic evaluation demonstrated a rapid payback period (< 1 month), several potential costs were not explicitly included in the analysis. These include unforeseen expenses such as temporary downtime caused by sensor malfunction, operator training for troubleshooting, and routine recalibration activities that may arise during long-term operation. Future economic assessments should incorporate these variables to produce a more comprehensive life-cycle cost model, capturing both direct and indirect financial impacts.

In terms of system flexibility, the current comparison with PLC-based architectures was limited to cost efficiency and synchronization accuracy. However, PLC systems offer long-term adaptability through reconfigurable logic and scalable I/O modules. In contrast, the proposed sensor–relay–timer configuration, while inexpensive and easy to install, provides limited reprogrammability. To enhance flexibility, subsequent research should integrate the control logic with microcontroller or IoT-based interfaces, allowing parameter tuning for variable container sizes, different conveyor speeds, or production line changes.

Furthermore, the scope of this study was restricted to a 19-L bottled-water filling line, which limits the generalizability of findings. Validation in other packaging formats, such as PET bottles, cartons, or drum containers would be essential to confirm the robustness of the proposed synchronization logic under differing mass, geometry, and conveyor dynamics. Expanding the study to multiple production environments will also provide stronger statistical evidence of transferability and reliability across the broader beverage and packaging sectors. Despite these limitations, the present results provide an empirical foundation demonstrating that a low-cost retrofit synchronization system can yield measurable mechanical and operational benefits under real industrial conditions. With appropriate scaling and system integration, the framework presented here can serve as a baseline for the wider adoption of affordable automation in small and medium-sized enterprises (SMEs).

Conclusions

This study demonstrated that a photodiode-based synchronization system can significantly improve the realibility and efficiency of a 19-liter gallon filling line, as evidenced by a 69,5 % reduction in starwheel load, a 50% decrease in gallon-fall incidents, and the elimination of one operator per shift. These results not only confirm the system's technical feasibility but also highlights its novel contribution as a low-cost, plug-and-play retrofit that delivers synchronization accuracy comparable to PLC-based systems while remaining accessible to resource-constrained manufacturers. However, the study has limitations. The evaluation was conducted under controlled operational conditions with a relatively small observation window (63 paired data points over three weeks), which may not fully capture variations in long-term wear, fluctuating production speeds, or unexpected machine faults. The open-loop design also restricts adaptability to dynamic disturbances.

Future research should therefore address these limitations by integrating closed-loop feedback control and predictive maintenance algorithms to improve resilience. Extending the approach to other packaging lines (e.g., PET bottles, cartons, or drums) and validating under multi-plant conditions would further establish generalizability. Incorporating IoT-based monitoring and wireless sensor networks could also strengthen alignment with

Industry 4.0 practices, enabling scalable deployment and smarter operational decision making.

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