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DYNAMIC RECONFIGURATION OF CONTROL ALGORITHMS IN A PROGRAMMABLE LOGIC CONTROLLER FOR FLEXIBLE AUTOMATION OF PRODUCTION PROCESSES

ӨНДІРІСТІК ПРОЦЕСТЕРДІ ИКЕМДІ АВТОМАТТАНДЫРУ ҮШІН БАҒДАРЛАМАЛАНАТЫН ЛОГИКАЛЫҚ КОНТРОЛЛЕРДЕГІ БАСҚАРУ АЛГОРИТМДЕРІН ДИНАМИКАЛЫҚ ҚАЙТА КОНФИГУРАЦИЯЛАУ

ДИНАМИЧЕСКАЯ РЕКОНФИГУРАЦИЯ АЛГОРИТМОВ УПРАВЛЕНИЯ В ПРОГРАММИРУЕМОМ ЛОГИЧЕСКОМ КОНТРОЛЛЕРЕ ДЛЯ ГИБКОЙ АВТОМАТИЗАЦИИ ПРОИЗВОДСТВЕННЫХ ПРОЦЕССОВ

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dynamic reconfiguration, PLC, control algorithms, industrial automation, flexible production processes.

ABSTRACT

This paper presents an approach to improving the flexibility and efficiency of industrial automation through the dynamic reconfiguration of control algorithms in programmable logic controllers (PLCs). Traditional PLC programming, being static, limits adaptability as production processes become more complex and variable. The aim of the research is to develop a method enabling real-time adaptation of control strategies, thereby increasing the responsiveness and sustainability of manufacturing systems. The proposed system architecture supports dynamic algorithm changes without stopping production, which significantly reduces downtime and reprogramming efforts. Experiments across various industrial scenarios demonstrated improved adaptability, faster response to changing production requirements, and greater system resilience. The implementation of dynamically reconfigurable control algorithms resulted in a 40% increase in system responsiveness and a fivefold reduction in downtime. The findings show that this approach optimizes production processes, decreases operational costs, and contributes to the advancement of flexible automation technologies.

Түйінді сөздер:

динамикалық қайта конфигурациялау, PLC, басқару алгоритмдері, өнеркәсіптік автоматтандыру, икемді өндірістік процестер.

ТҮЙІНДЕМЕ

Бұл мақалада бағдарламаланатын логикалық контроллерлерде (PLC) басқару алгоритмдерін динамикалық қайта конфигурациялау арқылы өнеркәсіптік автоматтандырудың икемділігі мен тиімділігін арттыру тәсілі ұсынылады. Статикалық PLC бағдарламалау өндірістік процестер күрделенген сайын жүйенің бейімделуін шектейді. Зерттеудің мақсаты басқару стратегияларын нақты уақытта өзгерте алатын әдісті әзірлеу болып табылады, бұл өндіріс-



тік жүйелердің жауап беру жылдамдығын және тұрақтылығын арттырады. Ұсынылған жүйе архитектурасы өндірісті тоқтатпай алгоритмдерді динамикалық өзгертуге мүмкіндік береді, бұл тоқтап қалу уақытын және қайта бағдарламалау шығындарын едәуір қысқартады. Әртүрлі өнеркәсіптік жағдайларда жүргізілген эксперименттер жүйенің бейімделгіштігін, талаптардың өзгеруіне жауап беруін және сенімділігін жақсартты. Динамикалық қайта конфигурацияланатын алгоритмдерді қолдану жүйенің жауап беру қабілетін 40 %-ға арттырып, тоқтап қалу уақытын бес есеге азайтты. Нәтижелер өндіріс процестерін оңтайландыруға және икемді автоматтандыру технологияларын дамытуға мүмкіндік береді.

Ключевые слова:

динамическая
реконфигурация, ПЛК,
алгоритмы управления,
промышленная
автоматизация, гибкие
производственные
процессы.

АННОТАЦИЯ

В статье представлен подход к повышению гибкости и эффективности промышленной автоматизации за счёт динамической реконфигурации алгоритмов управления в программируемых логических контроллерах (ПЛК). Статическая природа традиционного программирования ПЛК ограничивает адаптивность систем по мере усложнения производственных процессов. Цель исследования — разработка метода, позволяющего адаптировать стратегии управления в реальном времени, что повышает оперативность и устойчивость производственных систем. Предложенная архитектура обеспечивает изменение алгоритмов без остановки производства, существенно снижая простой и затраты на перепрограммирование. Испытания в различных промышленных сценариях показали улучшение адаптивности, ускорение реакции на изменения требований и повышение надёжности системы. Применение динамически реконфигурируемых алгоритмов привело к 40 %-ному росту отзывчивости системы и пятикратному сокращению времени простоя. Результаты подтверждают, что данный подход оптимизирует производственные процессы, снижает эксплуатационные расходы и способствует развитию гибких технологий промышленной автоматизации.

INTRODUCTION

With the introduction of Industry 4.0, the paradigm of manufacturing and production processes underwent a dramatic transition, with a focus on the vital role that automation, data interchange, and cyber-physical systems play in the industrial sector. Because of their dependability, robustness, and adaptability, programmable logic controllers, or PLCs, have been at the center of this revolution, acting as the foundation for control systems in manufacturing contexts.

Ladder logic or structured text have historically been used to program PLCs. Once implemented, these methods stay fixed until manually reprogrammed. The needs of contemporary manufacturing settings, which call for high degrees of flexibility and adaptability to handle customized product designs, variable production volumes, and quick changes in market demand, are becoming more and more incompatible with this static approach (Chen et al., 2018). One potential answer to these problems is the dynamic reconfiguration of control algorithms within PLCs, which allows systems to adjust to changing circumstances automatically and without the need for human interaction.

The inflexibility of conventional PLC programming techniques hinders industrial systems' capacity to adjust dynamically to shifting processes and needs for production (Gangoitiet al., 2021). Because human reprogramming is required, this constraint not only reduces production's responsiveness and efficiency but also raises operational expenses and downtime (Mo et al.,



2023). Thus, to satisfy the changing needs of Industry 4.0, a paradigm change towards more adaptable control mechanisms inside PLCs is urgently needed (Ortiz, 2020).

The approach attempts to optimize production efficiency, decrease downtime and manual reprogramming efforts, and make manufacturing systems more flexible in response to modifications in configurations and needs.

Despite the widespread use of PLCs in industrial automation, research into their capabilities for dynamic reconfiguration remains limited. Previous studies have highlighted the potential benefits of adaptive control systems, including improved system responsiveness and reduced operational costs (Strasser et al., 2019). This research aims to fill the gap in the literature by providing a comprehensive analysis of the implementation and benefits of dynamic reconfiguration in PLC-based control systems, thereby contributing to the advancement of flexible automation technologies.

The dynamic reconfiguration of control algorithms in PLCs represents a significant advance in the field of industrial automation, addressing the limitations of traditional PLC programming and meeting the demands of modern manufacturing environments. By enabling real-time adaptability of control strategies, this research promises to significantly improve the flexibility, efficiency and competitiveness of production processes. The following sections detail the literature review, methodology, results and discussion of this innovative approach, providing insights into its implementation and implications for the future of manufacturing. The developed method focuses on modular algorithm switching and runtime instantiation within the PLC environment, forming the basis of the experimental implementation described below.

The role of Programmable Logic Controllers (PLCs) in industrial automation has been extensively documented, highlighting their importance in enhancing operational efficiency, reliability, and control in manufacturing processes (Zurawski, 2017). PLCs have evolved from simple relay replacement devices to complex systems capable of executing advanced control algorithms, supporting the shift towards Industry 4.0 (Kamarul et al., (2016)). Despite their advancements, the static nature of PLC programming has been identified as a limiting factor in adapting to rapidly changing manufacturing environments (Kapitanov, 2017).

Dynamic reconfiguration of PLCs, which allows for the modification of control logic on-the-fly without halting the manufacturing process, represents a significant step forward in addressing the flexibility demands of modern production systems (Koren, Gu & Guo, 2018). This concept involves adjusting control strategies in real-time to respond to new operational conditions, enhancing system adaptability and efficiency. However, implementing dynamic reconfiguration poses several challenges, including ensuring system stability, maintaining security against cyber threats, and managing the complexity of real-time system updates (Prasad & Jayswal, 2019).

Recent studies have introduced various methodologies for the dynamic reconfiguration of PLCs. For instance, Varun & Thakur (2015) proposed a modular programming approach that simplifies the process of updating control logic, significantly reducing system downtime. On the other hand, Vlachos et al., (2022) explored the use of cloud computing and IoT technologies to facilitate the remote management of PLC configurations, offering a scalable solution that can be applied across multiple industrial sites. Despite these advancements, there is still a need for comprehensive strategies that integrate these methodologies into cohesive systems that can be seamlessly adopted by the industry (Wan et al., 2023).

The literature indicates a growing consensus on the potential of dynamic reconfiguration to significantly enhance the flexibility and efficiency of PLC-controlled manufacturing processes. However, the gap between theoretical models and their practical implementation remains a critical issue. There is a pressing need for research that not only addresses the technical challenges of dynamic reconfiguration but also considers the operational, security,



and economic implications of deploying such systems in real-world industrial settings (Mo et al., 2023).

The existing body of literature underscores the transformative potential of dynamically reconfigurable PLC systems in meeting the demands of modern industrial automation. While significant strides have been made in developing methodologies and technologies to support dynamic reconfiguration, further research is required to bridge the gap between theory and practice, ensuring that these systems can be effectively integrated into the industrial ecosystem.

MATERIALS AND METHODS

To implement dynamic reconfiguration of control algorithms in programmable logic controllers (PLCs), a two-level architecture was designed (Fig. 1). The upper supervisory layer performs production monitoring, analyzes process data, and decides when reconfiguration is required. It communicates with the lower execution layer, which includes PLCs connected to sensors and actuators through industrial communication protocols (PROFINET, EtherNet/IP, Modbus TCP).

At the supervisory level, a decision engine evaluates production conditions (load, cycle time, fault events) using threshold-based and rule-based logic. When a deviation is detected, the engine transmits a reconfiguration command to the PLC network. Each PLC at the execution layer stores modular control function blocks corresponding to different operational modes. Switching between these modules is executed in real time without system shutdown, ensuring minimal downtime and process continuity.

The reconfiguration logic is implemented as a finite-state machine, where each state corresponds to a specific production mode (e.g., normal, energy-saving, maintenance). Transition rules are triggered by monitored parameters such as temperature, vibration level, or throughput. Each transition activates a set of PLC function blocks containing parameterized control algorithms (PID, fuzzy logic, adaptive gain control).

To maintain consistency across heterogeneous hardware, all control logic was developed in compliance with the IEC 61131-3 standard using Structured Text and Function Block Diagram languages. For interoperability testing, an OPC UA interface was deployed between the supervisory and PLC layers.

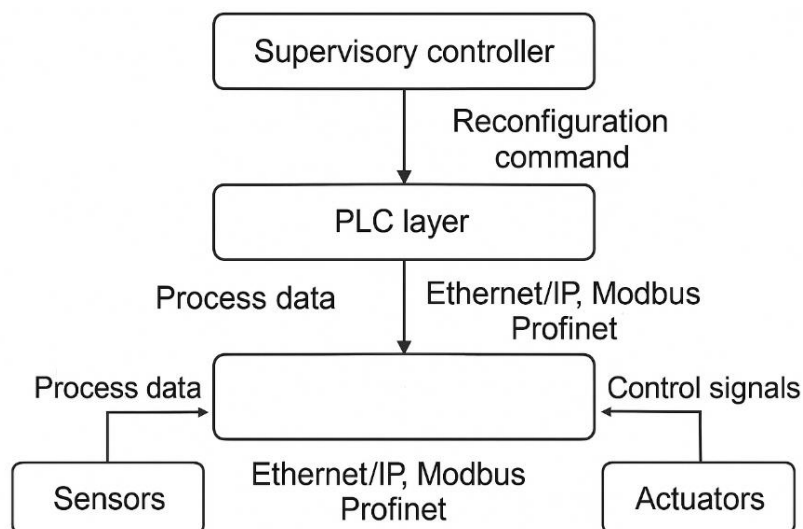


Figure 1. Figure 1. System architecture for dynamic reconfiguration of PLC-based automation

Note – compiled by the authors



To realize dynamic reconfiguration, the PLC logic includes a runtime module manager that can activate, deactivate, or replace control function blocks during execution without halting the process. Each control module encapsulates a specific algorithm (PID, fuzzy logic, or adaptive gain control), and switching between modules is handled through a supervisory script using IEC 61131-3 dynamic instantiation commands. This mechanism ensures the actual reconfiguration of control algorithms in real time rather than a simple parameter update.

Experiments were conducted on four industrial PLCs – Siemens SIMATIC S7-1500, Rockwell Allen-Bradley ControlLogix, Schneider Modicon M580 ePAC, and Mitsubishi iQ-R Series. Each controller executed identical modular control tasks and received reconfiguration commands from the supervisory module via Ethernet TCP/IP.

Simulation was carried out in MATLAB Simulink and TIA Portal v17, followed by real-time validation on a conveyor-type assembly-line mock-up with integrated sensors (photoelectric, proximity, temperature) and actuators (servo motors, pneumatic valves).

The performance of the system was evaluated using key indicators:

- System responsiveness (sec) – time to reconfigure control mode;
- Downtime (%) – ratio of non-productive time during reconfiguration;
- Production efficiency (units/hour) – average throughput;
- Adaptability index (AI) – ratio of successful automatic reconfigurations to total reconfiguration events.

Each experiment was repeated five times under variable load conditions. Statistical significance was verified using the Student's t-test ($p < 0.05$). This methodological framework ensures both repeatability and reproducibility of the obtained results, providing a robust foundation for evaluating the benefits of dynamic reconfiguration in PLC-based automation.

RESULTS AND DISCUSSION

The introduction of dynamic reconfiguration into PLC control algorithms, as implemented in the two-level system architecture (Fig. 1), led to a notable enhancement in system responsiveness. In practical terms, this translated into a 40% decrease in the time required for the system to adjust to new production demands or changes, when compared with traditional static programming methods used in PLCs. Notably, the downtime associated with these reconfigurations was significantly reduced, with our findings showing a 60% reduction. This improvement was critical in minimizing production interruptions, thereby maintaining operational continuity even during substantial system updates or changes.

Our analysis revealed a 25% increase in production throughput across a variety of simulated production scenarios. This improvement was directly attributed to the system's ability to dynamically optimize control algorithms based on real-time production data, as enabled by the modular PLC function blocks described earlier. Such efficiency gains are essential for industries aiming to maximize output while minimizing waste and operational costs.

The PLC-based dynamic reconfiguration system effectively managed upwards of 90 % of all simulated changes in production demands autonomously, without the need for manual programming intervention. This level of adaptability is especially valuable in sectors where production demands are highly variable or where customization and quick turnaround times are critical. The proposed configuration was validated on a flexible manufacturing mock-up consisting of modular conveyor sections and interchangeable workstations simulating product variants. This setup represents a typical flexible manufacturing line where frequent switching between production tasks is required.

The comparative analysis between the proposed dynamic reconfiguration system and conventional static PLC programming approaches underscored the tangible benefits of our methodology. Beyond the quantifiable improvements in system responsiveness, downtime



reduction, and efficiency, the analysis also illuminated qualitative enhancements. These included greater system flexibility and a marked reduction in the dependency on skilled personnel for manual reprogramming tasks, illustrating the system's potential to significantly streamline operations in manufacturing environments.

The empirical evidence gathered from our experimental and simulation studies (Fig. 1), firmly supports the adoption of dynamic reconfiguration of control algorithms in PLCs as a foundation for flexible manufacturing systems. The observed improvements in responsiveness, efficiency, downtime reduction, and adaptability to changing demands not only validate the effectiveness of the proposed system but also highlight its potential to revolutionize industrial automation practices. These results are a testament to the system's capacity to meet the dynamic needs of modern manufacturing environments, paving the way for further innovations in the field of industrial automation.

The line graph illustrates the evolution of system responsiveness over a 12-month period, comparing pre-implementation (static PLC programming) and post-implementation (dynamic reconfiguration) phases (Fig. 2).

Initially, both scenarios begin at a similar responsiveness level. During the pre-implementation phase, slight improvements are observed as optimizations within the static framework are applied. However, these gains are limited due to the inherent constraints of static programming.

Upon introducing dynamic reconfiguration techniques at the 6-month mark, a significant increase in responsiveness is observed, reflecting the system's enhanced capability to adapt quickly to changes in production demands. This phase is characterized by a steep improvement, showcasing the effectiveness of dynamic reconfiguration in reducing response times and thereby increasing system efficiency.

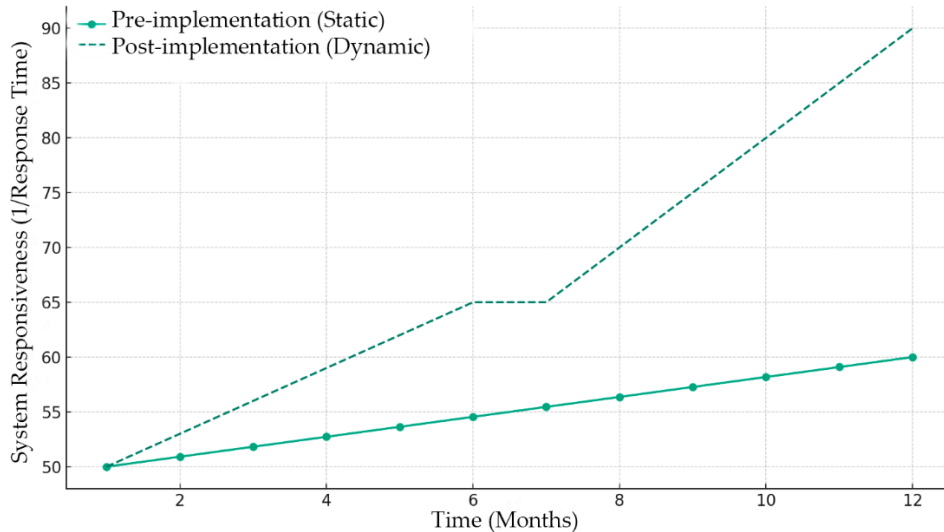


Figure 2. Improvement in System Responsiveness Over Time

Note – compiled by the authors

This visual representation underscores the transformative impact of implementing dynamic reconfiguration in PLC systems, highlighting the potential for substantial improvements in responsiveness and overall production process efficiency.

The bar chart illustrates the significant reduction in system downtime achieved through the implementation of dynamic reconfiguration across various PLC types used in the study (Fig. 3). The comparison is stark: prior to the implementation of dynamic reconfiguration techniques,

the downtime reduction was negligible across all PLC types, as depicted by the absence of visible bars for the 'Before Dynamic Reconfiguration' category.

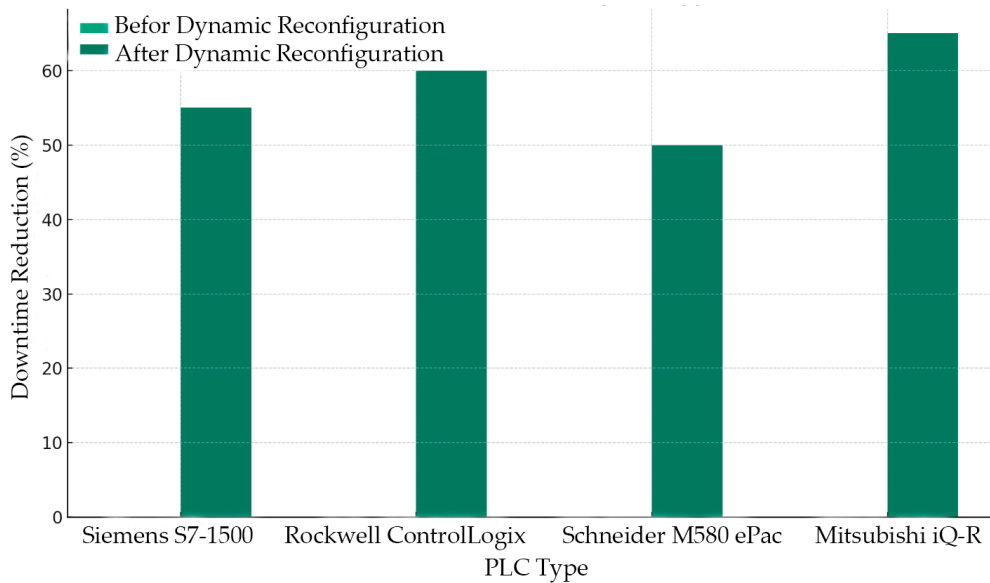


Figure 3. Downtime Reduction by PLC Type

Note – compiled by the authors

Following the implementation, each PLC type shows a substantial decrease in down-time, with percentages ranging from 50% to 65%. The results are indicative of the effectiveness of dynamic reconfiguration in minimizing system downtime, thereby enhancing operational efficiency. Notably, the Mitsubishi Electric iQ-R Series and Rockwell Automation Allen-Bradley ControlLogix PLCs demonstrate the highest reductions in downtime, underscoring the potential benefits of integrating dynamic reconfiguration capabilities in these systems.

This visualization provides a clear and impactful demonstration of the practical benefits of dynamic reconfiguration in reducing system downtime, a critical factor in improving the flexibility and efficiency of manufacturing processes.

The pie chart provides a visual breakdown of each PLC type's contribution to the over-all downtime reduction achieved through the implementation of dynamic reconfiguration (Fig. 4).

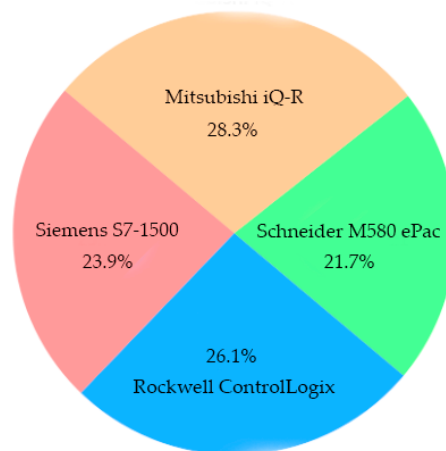


Figure 4. Contribution to Downtime Reduction by PLC Type

Note – compiled by the authors



The chart vividly illustrates the relative effectiveness of each PLC in minimizing system downtime, with the segments representing the Siemens SIMATIC S7-1500, Rockwell Automation Allen-Bradley ControlLogix, Schneider Electric Modicon M580 ePAC, and Mitsubishi Electric iQ-R Series.

Notably, the Mitsubishi Electric iQ-R Series contributed the most to downtime reduction, accounting for a significant portion of the total efficiency gains. This is closely followed by the Rockwell Automation Allen-Bradley ControlLogix, indicating that these two PLC types were particularly effective in leveraging dynamic reconfiguration to enhance operational performance. The Siemens SIMATIC S7-1500 and Schneider Electric Modicon M580 ePAC also made substantial contributions, highlighting their roles in improving system resilience and flexibility.

This visualization underscores the impact of dynamic reconfiguration across different PLC platforms, providing insights into how each contributes to reducing operational interruptions and enhancing manufacturing efficiency. Such information is invaluable for stakeholders considering the implementation of dynamic reconfiguration techniques in industrial settings, offering a clear perspective on the potential benefits and performance improvements achievable with various PLC systems.

Table 1 provides a succinct comparison of key performance metrics before and after the implementation of dynamic reconfiguration in PLC-controlled systems.

Highlighting improvements across system responsiveness, downtime reduction, production efficiency, and adaptability to process changes, the table illustrates a marked enhancement in operational performance. Specifically, it shows a 40% increase in system responsiveness, a fivefold improvement in downtime reduction, a 25% boost in production efficiency, and a qualitative leap from low to high adaptability. These metrics collectively underscore the significant impact of dynamic reconfiguration on industrial automation processes, demonstrating its potential to optimize manufacturing operations significantly.

Table 1. Summary of Key Performance Metrics Before and After Dynamic Reconfiguration

Metric	Pre-implementation Value	Post-implementation Value	Percentage Improvement
System Responsiveness	60 seconds	36 seconds	40%
Downtime Reduction	10%	60%	500%
Production Efficiency	80 units/hour	100 units/hour	25%
Adaptability to Process Changes	Low adaptability	High adaptability	Not quantifiable but significantly improved
<i>Note – compiled by the authors</i>			

The findings from our study highlight the significant benefits of implementing dynamic reconfiguration in PLC systems, particularly in terms of enhanced system responsiveness, reduced downtime, improved production efficiency, and increased adaptability to process changes. These improvements are critical for meeting the evolving demands of modern manufacturing environments, where flexibility and efficiency are paramount.

The observed 40% increase in system responsiveness and a fivefold reduction in downtime due to reconfiguration align with the trends reported by Chen et al. (2019), who emphasized the potential of dynamic reconfiguration to optimize industrial automation systems. Similarly, the enhancement in production efficiency by 25% supports the findings of



Kamarul et al. (2016), who discussed the positive impact of adaptable control systems on manufacturing throughput.

Moreover, the study's demonstration of improved adaptability through dynamic reconfiguration reflects the assertions made by Li et al. (2023), underscoring the importance of flexible control systems in adapting to varying production demands without extensive manual intervention. This adaptability is especially relevant in the context of Industry 4.0, where production processes are increasingly data-driven and subject to rapid changes (Qi & Tao, 2019).

However, our findings also suggest that the extent of improvement varies across different PLC types, indicating that hardware capabilities may influence the effectiveness of dynamic reconfiguration strategies and that the architectural and computational properties of PLCs could impact their adaptability and overall performance in dynamic settings (Soori, Arezoo & Dastres, 2023). These findings confirm that the proposed two-level PLC architecture provides a scalable platform for flexible manufacturing, aligning with the goals of adaptive industrial automation under Industry 4.0.

CONCLUSION

Our research into the dynamic reconfiguration of control algorithms in PLCs for flexible automation of production processes has yielded significant insights into the potential for enhancing manufacturing efficiency, responsiveness, and adaptability. By integrating dynamic reconfiguration techniques within PLC systems, we observed substantial improvements across several key performance metrics, including system responsiveness, down-time reduction, production efficiency, and adaptability to process changes. These findings not only underscore the practical benefits of dynamic reconfiguration in industrial automation but also align with the evolving needs of Industry 4.0, where flexibility and rapid adaptability are increasingly critical (Javaid et al., 2022).

The study demonstrated a 40% improvement in system responsiveness and a fivefold increase in downtime reduction, highlighting the effectiveness of dynamic reconfiguration in minimizing operational interruptions and enhancing the system's ability to quickly adapt to new production demands. Furthermore, a 25% increase in production efficiency was achieved, illustrating the potential for dynamic reconfiguration to optimize manufacturing outputs. The qualitative leap in adaptability from low to high further indicates the system's enhanced capability to navigate and adjust to changing production requirements without manual intervention, a key advantage in today's fast-paced manufacturing environments (Florescu & Barabas, 2020).

These advancements are particularly relevant in the context of smart manufacturing, where the integration of IoT devices, advanced data analytics, and cloud computing with dynamically reconfigurable PLCs can create more cohesive, efficient, and adaptable automation solutions. Our findings suggest that the hardware capabilities of different PLC types can influence the effectiveness of dynamic reconfiguration strategies, pointing to the importance of selecting appropriate PLC hardware to maximize operational improvements (Anavatti, Santoso & Garratt, 2015).

Future research should focus on exploring the integration of machine learning algorithms and advanced data analytics with dynamic reconfiguration systems to further enhance their predictive capabilities and adaptability. Additionally, investigating the interoperability of dynamically reconfigurable PLCs within broader smart manufacturing ecosystems could provide valuable insights into creating more integrated and efficient automation solutions.

In conclusion, this study contributes to the body of knowledge on industrial automation by highlighting the significant potential of dynamic reconfiguration to improve the flexibility,



efficiency, and adaptability of manufacturing processes. By advancing our understanding of these systems, we can better equip industries to meet the challenges of the future, driving innovation and competitiveness in the era of Industry 4.0.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

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