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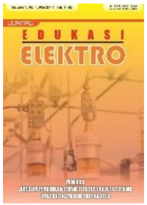

Bridging Control System Education and Industrial Practice through a Real-Time Control System Architecture

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Abstract— The limited accessibility, high cost, and low scalability of industrial control platforms constrain hands-on learning in automation education. This study presents a real-time control system architecture that bridges instructional requirements with industrial control principles through deterministic execution and structured logic representation. The system integrates ladder-based programming with cyclic scan execution and direct I/O mapping to ensure consistent real-time operation. A design and development methodology based on the adopted-ADDIE framework was employed to guide system realization and validation. The system was evaluated through expert-based assessment using a four-point Likert scale, followed by feasibility, content validity, and reliability analyses. Results indicate high technical feasibility, with technical quality reaching 83.04% and display quality 84.38% (very feasible), while instructional aspects range from 75.00% to 79.55% (feasible). Content validity achieved Aiken's V values of 0.852 (very high) and 0.716 (high), with reliable expert agreement (Sig. > 0.05). These findings validate the proposed architecture as a scalable and reliable control system platform for automation learning.

Keywords: programmable logic controllers, engineering education, industrial automation, real-time control.

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1 Introduction

The increasing integration of automation technologies in industrial systems has intensified the demand for workforce competencies that extend beyond theoretical understanding toward practical control system implementation [1], [2]. In vocational education, particularly in industrial automation programs, this requirement translates into the need for learning environments that enable direct interaction with control hardware and real-time system behavior [3], [4], [5]. However, the effectiveness of such learning environments is often constrained by the limited availability of industrial-grade equipment, high procurement costs, and restricted access to hands-on practice. These constraints create a discrepancy between the competencies required in industrial contexts and those developed within educational settings.

Programmable Logic Controllers (PLCs) remain a fundamental platform for industrial automation, characterized by deterministic control execution [6], modular input-output architecture [7], and reliability in real-time operation. Despite their relevance, the adoption of PLC-based learning in vocational education faces practical limitations. Industrial PLC systems are typically cost-intensive and not easily scalable for classroom use, resulting in shared usage among students and reduced opportunities for repeated experimentation. Furthermore, conventional PLC programming environments often introduce additional complexity for beginners, particularly when transitioning from text-based programming paradigms to control logic design [8]. These factors collectively hinder the development of procedural and operational competencies that are essential in automation engineering.

From a learning system perspective, effective control system education requires not only access to hardware but also alignment between programming abstraction and cognitive readiness of learners [9], [10], [11], [12]. The difficulty experienced by students in understanding text-based programming structures indicates a mismatch between instructional tools and learner capabilities [13], [14]. Visual programming approaches, such as ladder diagram representation [15], provide a more structured and intuitive mechanism for expressing control logic, closely resembling industrial practices while reducing cognitive load. However, the availability of learning platforms that integrate ladder-based programming with affordable and scalable hardware remains limited.

Recent developments in microcontroller-based systems provide an opportunity to address these challenges by offering flexible and cost-effective alternatives to conventional PLC platforms [16]. Microcontrollers can emulate key PLC functionalities, including cyclic scan execution, digital input–output processing, and real-time control logic implementation. Nevertheless, many existing implementations focus primarily on hardware prototyping [17][18][19] without adequately addressing instructional integration, system architecture consistency, and validation of performance in an educational context. As a result, the potential of microcontroller-based PLC alternatives as structured learning media remains underexplored.

This study addresses these limitations by developing a PLC-like control system, referred to as the PLC Outseal, which integrates ladder diagram programming with microcontroller-based execution in a unified framework. The proposed system is designed not only as a functional control platform but also as an instructional medium that aligns technical implementation with learning requirements. The development process is structured using a systematic design methodology, ensuring that the system is derived from identified constraints in real learning environments and validated through quantitative evaluation.

The novelty of this work lies in the integration of three key aspects within a single framework. First, the study presents a system-level design that transforms a general-purpose microcontroller into a PLC-like platform with deterministic control behavior and modular input-output configuration. Second, it incorporates ladder diagram-based programming as a primary interface to reduce cognitive complexity while maintaining alignment with industrial control practices. The results demonstrate that the proposed system achieves high technical feasibility, with strong performance in hardware–software integration and operational stability, while also satisfying the requirements for instructional use. These findings indicate that the PLC Outseal system can serve not only as a learning medium but also as a product platform for basic automation applications. By bridging the gap between affordability, usability, and technical functionality, this study contributes a practical and scalable approach to enhancing control system education in vocational settings.

2 Method

This study employs a structured design and development methodology based on the ADDIE framework, consisting of five sequential stages: analysis, design, development, implementation, and evaluation [20], [21]. As illustrated in Figure 1, the methodology is organized as a system-oriented workflow that transforms identified learning constraints into a validated control system through iterative refinement. The framework explicitly defines the relationship between input, process, output, and outcome, ensuring methodological transparency and engineering rigor.

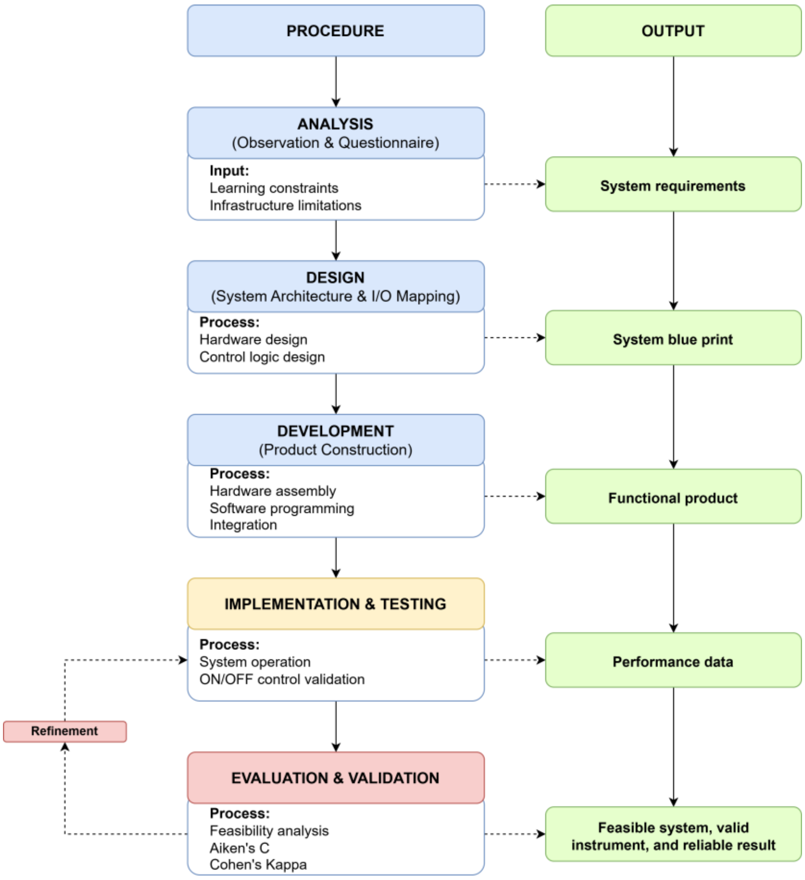

Figure 1. Research methodology framework (ADDIE-adopted model)

The process begins with the analysis stage, where contextual data are collected through direct observation and questionnaire-based assessment. This stage aims to identify limitations in learning media, infrastructure, instructional approaches, and student competencies. The output of this stage is a set of system requirements that serve as the foundation for subsequent design activities. The design stage translates the identified requirements into a structured system architecture, including hardware configuration, input-output mapping, and control logic design. This stage establishes the conceptual blueprint of the Outseal PLC system, ensuring alignment between technical functionality and instructional objectives.

The development stage involves the realization of the designed system through hardware assembly, ladder-based programming, and hardware–software integration. The output of this stage is a functional product capable of executing control logic in a real-time environment. The implementation stage focuses on the architectural validation of the developed system. As indicated in Figure 1, the system is subjected to operational validation using a ON/OFF control scenario, which serves as a structured test case to verify the correctness of the core architectural mechanisms, namely cyclic scan execution, I/O mapping consistency, and hardware-software synchronization. This approach is consistent with the research and development (R&D) orientation of this study, wherein the primary objective is to validate the proposed system architecture through a controlled and reproducible scenario. The resulting output of this stage is performance data that reflect the architectural integrity and operational reliability of the developed platform.

The evaluation stage represents a critical phase in which the system is assessed using quantitative methods [22]. The evaluation process includes feasibility analysis, content validity assessment, and reliability testing. A feedback mechanism, labelled as refinement in Figure 1, connects the evaluation stage back to earlier stages, indicating that the development process is iterative rather than strictly linear. This iterative loop enables continuous improvement of both technical and instructional aspects of the system [23], [24]. The outcome of the methodology is a validated system characterized by technical feasibility, instrument validity, and reliability of evaluation results. This outcome demonstrates that the developed Outseal PLC system not only functions as intended but also meets the requirements for implementation as both a learning medium and a product control platform.

2.1 Data Collection Methods

Data collection was conducted using a combination of observational techniques and structured questionnaires to capture both contextual and quantitative information [20]. Observation was used to identify real-world constraints in the learning environment, including limitations in equipment availability, instructional practices, and student engagement. These findings form the primary input to the analysis stage. Quantitative data were obtained through expert-based evaluation using structured questionnaires based on a four-point Likert scale, where scores range from 1 (not feasible) to 4 (very feasible) [21]. This scale was selected to eliminate neutral responses and to ensure decisive expert judgment. The evaluation involved experts in media and instructional content, where the media assessment focuses on technical and visual aspects, while the material assessment evaluates learning outcomes, content completeness, and instructional impact.

2.2 Feasibility Analysis

The feasibility of the developed system was evaluated by converting Likert-scale scores into percentage values to enable standardized comparison across evaluation aspects. The percentage of feasibility P is calculated by the first equation [21]:

$$P = \frac{\sum X}{X_{\max}} \times 100\% \tag{1}$$

where $\sum X$ represents the total score obtained from expert evaluations, and $X_{\max}$ denotes the maximum possible score across all assessment items. The resulting percentage values were interpreted using predefined feasibility criteria derived from the ideal mean and standard deviation, allowing classification of the system into categories such as very feasible, feasible, and not feasible. This analysis provides a normalized measure for comparing different evaluation aspects within the system.

2.3 Content Validity Analysis

Content validity of the evaluation instruments was assessed using Aiken's V coefficient, which measures the degree of agreement among experts regarding the relevance of each item. The coefficient V is defined by the second equation [22]:

$$V = \frac{\sum s}{n(c-1)} \tag{2}$$

where $s = r - l_0$, r represents the rating assigned by each expert, l_0 denotes the lowest possible rating score, c is the number of rating categories, and n is the number of experts. The resulting value of V ranges from 0 to 1, where higher values indicate stronger agreement and higher content validity. This analysis ensures that the evaluation instrument accurately represents the constructs being measured.

2.4 Reliability Analysis

The reliability of the evaluation instruments was examined through inter-rater reliability analysis to assess the consistency of expert judgments. This analysis was performed using Cohen's Kappa coefficient (κ), which measures the level of agreement between evaluators beyond chance. The coefficient is defined by the 3rd equation [23].

$$\kappa = \left[\frac{P_O - P_e}{1 - P_e}\right] \tag{3}$$

where P_o represents the observed agreement between raters, and P_e denotes the expected agreement by chance. A higher value of κ indicates stronger agreement between evaluators. Statistical significance was determined based on the associated probability value. A significant level greater than 0.05 indicates that there is no statistically significant disagreement between raters. The agreement between evaluators can be considered consistent and the evaluation results are deemed reliable.

3 Result and Discussion

This section presents the results of the study organized into four interconnected parts. The discussion begins with a needs analysis that identifies the contextual constraints driving system development and derives the corresponding design implications. It is then followed by a description of the proposed system architecture and its operational framework, along with an account of the hardware-software integration that enables real-time control execution. Finally, the section presents a comprehensive validation through expert-based feasibility, content validity, and reliability analyses.

3.1 Need Analysis and Design Implications

The needs analysis was conducted through direct classroom observations and questionnaire-based data collection involving students in the Industrial Automation Engineering program. The analysis aimed to identify constraints in existing PLC learning practices and to derive system design requirements aligned with both technical and pedagogical needs. The synthesized results are presented in Table 1.

Table 1. Needs analysis and derived design implications

System Aspect	Identified Constraints	Empirical Evidence	Operational Impact	Design Implications
Learning Media	Limited availability of PLC and Arduino-based trainers	Students were required to share devices during practical sessions	Reduced frequency and duration of hands-on activities	Development of a low-cost, replicable PLC training system
Learning Facilities	Suboptimal condition of computer units	Several computers required maintenance and were not fully operational	Inefficient execution of software-based learning activities	Design of a system compatible with standard computing environments
Instructional Approach	Predominantly theory-oriented learning	Limited use of demonstrations and practical exercises	Low engagement in applied learning tasks	Integration of practice-oriented and demonstration-based learning scenarios
Student Engagement	Passive participation during learning activities	Minimal interaction observed in discussions and collaborative work	Limited active involvement in the learning process	Development of interactive and student-centered learning media
Programming Competency	Difficulty in understanding text-based programming (C/C++)	Students reported challenges in constructing program logic using textual syntax	Barriers in mastering control system concepts	Adoption of ladder diagram-based programming interface
Accessibility	High cost of industrial PLC systems	Students lacked access to PLC devices outside the classroom	Restricted opportunities for independent practice	Development of an affordable and portable PLC alternative

The results indicate that constraints in PLC learning are not limited to a single dimension but occur across technical infrastructure, instructional design, and learner competency. The limited availability of training equipment, combined with the high cost of industrial PLC systems, reduces students' opportunities to engage in repeated and independent hands-on practice. This limitation directly affects the development of procedural and operational skills, which are essential in automation-related competencies. Similar findings have been reported in vocational education studies, where access to practical training tools significantly influences skill acquisition and learning outcomes [24], [25]

From an instructional perspective, the dominance of theory-oriented teaching methods contributes to low student engagement and limited participation in practical activities. The observed preference for demonstration-based and hands-on learning indicates a mismatch between instructional delivery and the applied nature of PLC competencies. Prior studies have emphasized that experiential and practice-oriented learning environments are critical in engineering education, as they facilitate deeper understanding and improve learner engagement [26].

In terms of programming competency, the difficulty experienced by students in using text-based programming languages such as C/C++ highlights the presence of cognitive barriers in understanding control logic. Students tend to rely on more structured and visual representations when constructing program logic. The preference for ladder diagram programming suggests that visual programming paradigms can reduce cognitive load and support conceptual understanding in technical learning contexts [27]

Furthermore, the issue of accessibility remains a critical factor. The high cost of industrial PLC systems limits students' ability to practice outside formal learning environments, thereby restricting opportunities for independent skill development. This condition reinforces the need for affordable and portable learning solutions that can extend learning beyond the classroom setting.

Based on these findings, the design of the proposed system is directed toward addressing the identified constraints through a problem-driven approach. The system is developed using a microcontroller-based architecture to ensure cost efficiency, while incorporating ladder diagram programming to enhance usability and reduce cognitive complexity. In addition, the system is designed to support interactive and hands-on learning activities, aligning with the requirements of vocational education and industrial skill development.

3.2 System Architecture and Operational Framework of Outseal PLC

The Outseal PLC system is designed as a microcontroller-based control platform that functionally emulates a conventional programmable logic controller (PLC) by integrating ladder diagram programming with real-time hardware execution. The overall system architecture, illustrated in Figure 2, adopts a layered structure that enables a clear separation between programming, control processing, and physical input-output subsystems.

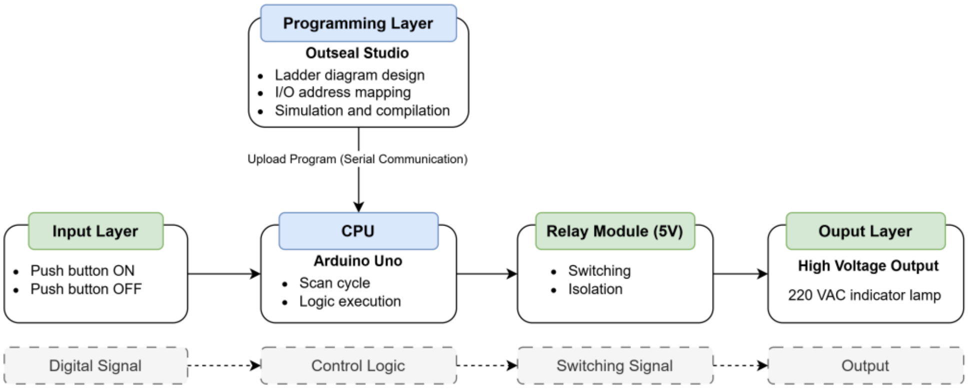

Figure 2. Layered system architecture of Outseal PLC

Based on Figure 2, the system consists of five interconnected layers: programming layer, input layer, control processing unit, relay module, and output layer. This layered architecture defines the structural organization of the system and establishes a systematic signal flow, allowing control logic developed at the software level to be translated into physical control actions. The programming layer utilizes Outseal Studio as a ladder diagram-based development environment, where control logic is constructed, mapped to input-output addresses, and validated through simulation prior to deployment. The compiled program is then transmitted to the microcontroller via serial communication, enabling direct implementation of the validated control logic. The control processing unit, implemented using an Arduino Uno, executes the control logic through a continuous scan cycle. The relay module (5V) functions as an interface between the low-voltage control signals and the high-voltage output system, providing both switching and electrical isolation. Finally, the output layer delivers the control results to the load, such as a 220 VAC indicator lamp. This structural design abstracts low-level programming complexity while preserving logical consistency across system components.

While Figure 2 describes the structural architecture of the system, the operational mechanism is further illustrated in Figure 3, which presents the integrated workflow from control logic development to real-time execution.

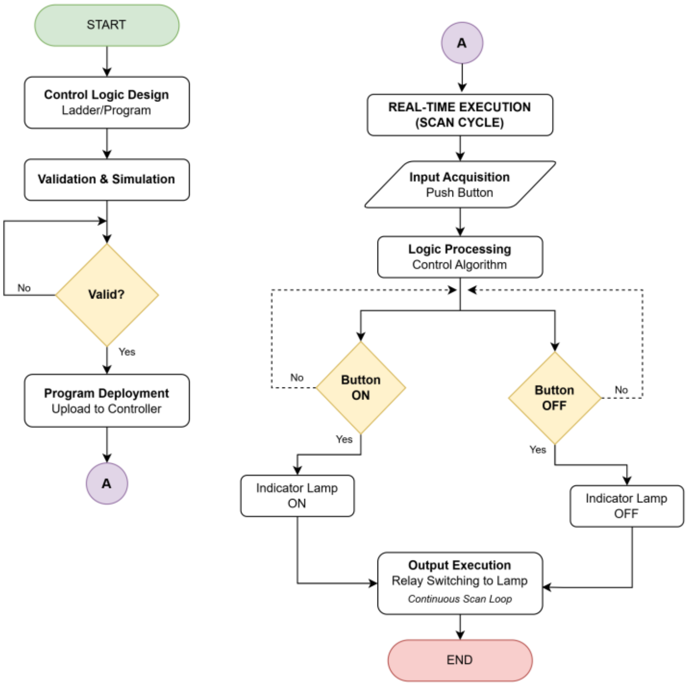

Figure 3. Integrated operational workflow of the Outseal PLC

Based on Figure 3, the system operates through two interconnected phases: the development and deployment phase, and the real-time execution phase. In the first phase, control logic is designed using ladder diagram representation, followed by compilation and simulation-based validation. If the validation results are not satisfactory, the process iterates until the desired logic behavior is achieved. Once validated, the program is deployed to the microcontroller, establishing the control logic for system operation.

The second phase represents the real-time execution mechanism, where the system operates based on a cyclic scanning process. During operation, the control processing unit continuously performs input acquisition, logical processing, and output updating. Input signals generated from push-button interactions are read by the system, processed according to the programmed logic, and translated into control signals that drive the relay module. The relay module functions as an interface layer, enabling safe switching of high voltage loads through electrical isolation. The output layer executes the final control action, where indicator lamps are activated or deactivated in accordance with the logical conditions defined in the program. It should be noted that the operational workflow does not include a termination state, as the system follows a continuous execution model inherent to PLC-based control systems. The cyclic scan mechanism ensures deterministic and real-time system response, which is essential for control applications.

The physical implementation of the system reflects the defined architecture through a compact and modular configuration. The separation between input, processing, and output sections reduces wiring complexity and enhances system readability, facilitating both assembly and troubleshooting processes. The operational framework follows a sequential workflow from program design to real-time execution. Control logic is first developed and validated through simulation, then deployed to the microcontroller, followed by hardware assembly and commissioning. Experimental results confirm that the system maintains consistency between simulated logic behavior and physical execution, particularly in ON/OFF control scenarios, indicating reliable synchronization between software and hardware domains.

From an engineering perspective, the proposed architecture demonstrates an effective transformation of a general-purpose microcontroller into a PLC-like control system. The integration of ladder diagram programming with embedded control execution provides a simplified yet functionally representative alternative to conventional PLC systems. This approach reduces system complexity while maintaining essential control characteristics, including real-time processing, modular input–output configuration, and deterministic control behavior

3.3 Hardware-Software Integration of Outseal PLC

The hardware–software integration of the PLC Outseal system is designed to ensure a seamless translation of ladder-based control logic into real-time physical execution. This integration is achieved through a direct mapping between software-defined control logic and microcontroller-based input-output interfaces [17], supported by a consistent and modular hardware configuration. The integration process begins with the definition of the hardware architecture through a structured component layout, as shown in Figure 4. The layout illustrates the spatial arrangement of the Arduino Uno as the control processing unit, the relay module as the output interface, and the input module consisting of push-button switches mounted on a printed circuit board. This modular arrangement establishes a clear separation between input, processing, and output subsystems, which enhances system readability, simplifies assembly, and reduces potential wiring errors.

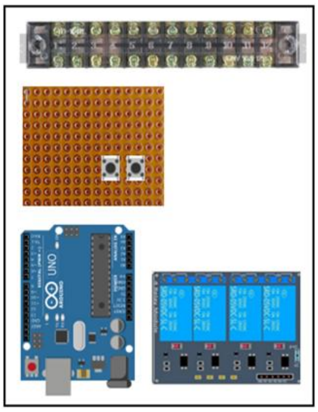

Figure 4. Component layout design of Outseal PLC

To ensure functional connectivity between subsystems, the I/O wiring configuration is defined as presented in Figure 5. The wiring design specifies the connection between input devices, control unit, and output loads, including the mapping of push-button inputs to digital pins and relay outputs to AC loads. This configuration ensures that each logical variable defined in the control program corresponds directly to a physical signal path in the hardware system, thereby enabling deterministic signal transmission from input acquisition to output execution. The consistency between the designed configuration and its physical realization is validated through the implemented product. The hardware implementation demonstrates that the actual wiring and component arrangement strictly follow the predefined design. This design-to-implementation consistency is essential to ensure that the control logic developed in the software environment can be executed reliably in the physical system without deviation.

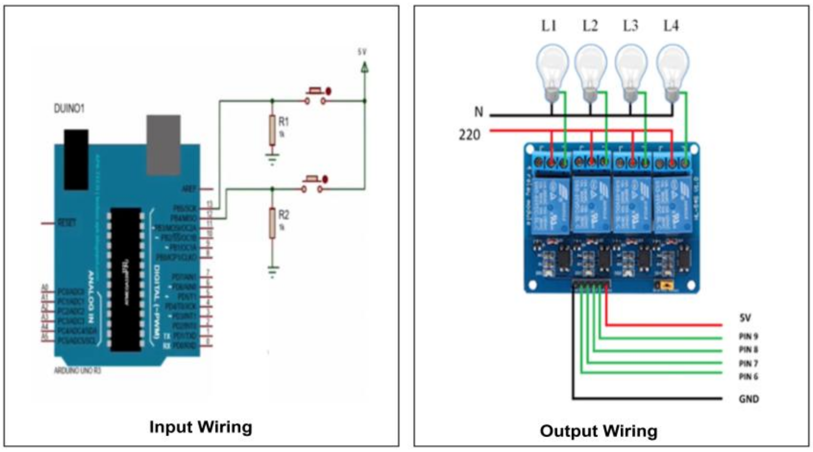

Figure 5. I/O Wiring configuration of Outseal PLC

From the software perspective, the control logic is developed using Outseal Studio, as illustrated in Figure 6. The ladder diagram interface allows users to construct control logic using graphical representations, while the integrated simulation environment provides a platform for validating logical behaviour prior to deployment. Each element in the ladder diagram is mapped to corresponding hardware inputs and outputs, establishing a direct link between virtual logic and physical execution. The simulation results shown in Figure 6 confirm that the defined control logic produces the expected output behaviour under given input conditions. This validation step ensures that logical errors are minimized before the program is deployed to the hardware system. Following successful validation, the compiled program is uploaded to the Arduino Uno via serial communication, embedding the control logic into the microcontroller.

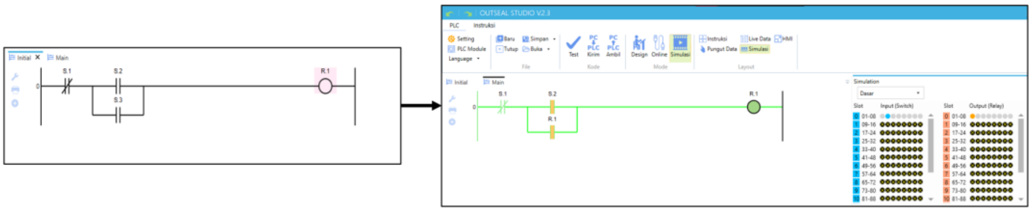

Figure 6. Ladder diagram programming and simulation environment in Outseal Studio

During system operation, the microcontroller executes the control logic using a cyclic scanning mechanism consisting of input acquisition, logical processing, and output updating. This execution model ensures real-time responsiveness and deterministic control behavior, consistent with the operational principles of conventional PLC systems. Input signals generated through push-button interactions are continuously monitored, processed according to the ladder logic, and translated into control signals that drive the relay module. The relay module functions as an interface layer that performs signal amplification and electrical isolation, enabling the microcontroller to control high-voltage AC loads safely. The output execution is realized through the switching of indicator lamps, where the system successfully performs ON/OFF control operations based on the programmed logic.

Experimental results demonstrate that the integrated system operates consistently across software and hardware domains. The control logic validated in the simulation environment is accurately executed in the physical system, as evidenced by the correct response of output loads to input commands. The system maintains stable performance during continuous operation, indicating reliable synchronization between programming, control processing, and hardware interfacing. From an engineering perspective, the proposed integration framework demonstrates an effective transformation of a general-purpose microcontroller into a PLC-like control system. The use of ladder diagram programming abstracts low-level coding complexity while preserving logical accuracy and control functionality [27]. At the same time, the direct mapping between software logic and hardware interfaces ensures deterministic execution and system reliability. Furthermore, the modular architecture of the system supports scalability [7], allowing additional I/O channels to be incorporated without altering the core control structure. This indicates that the Outseal PLC system is not only suitable as a learning platform but also has potential as a prototyping tool for basic industrial automation applications

3.4 System Validation and Feasibility Evaluation based on Expert Assessment

The validation and feasibility analysis of the Outseal PLC system were conducted through expert-based evaluation to assess both the technical quality of the media and the adequacy of instructional materials. The evaluation employed structured instruments with Likert-scale measurements, followed by quantitative analysis to determine feasibility, validity, and reliability.

The results of the expert-based feasibility evaluation are presented in Table 2 and further illustrated in Figure 7. The findings indicate that the media aspect achieved a “very feasible” category across all evaluated sub-aspects. Specifically, the technical quality obtained a mean score of 46.5 out of a maximum score of 56, corresponding to 83.04%, while the display quality achieved 84.38%. As visualized in Figure 7, both sub-aspects of the media domain consistently demonstrate higher percentage values compared to the material domain. These results confirm that the developed system exhibits a high level of technical robustness, including stable functionality, reliable operation, and effective hardware–software integration. The slightly higher percentage in display quality further suggests that the system provides a clear visual structure and usability, supporting intuitive user interaction during operation.

Table 2. Expert-based feasibility evaluation of Outseal PLC

Aspect	Sub-Aspect	Items (n)	Mean Score	Max Score	Percentage (%)	Category
Media	Technical Quality	14	46.5	56	83.04	Very Feasible
	Display Quality	4	13.5	16	84.38	Very Feasible
Material	Learning Outcomes	11	35	44	79.55	Feasible
	Content Completeness	3	9	12	75.00	Feasible
	Learning Impact	3	9.5	12	79.17	Feasible

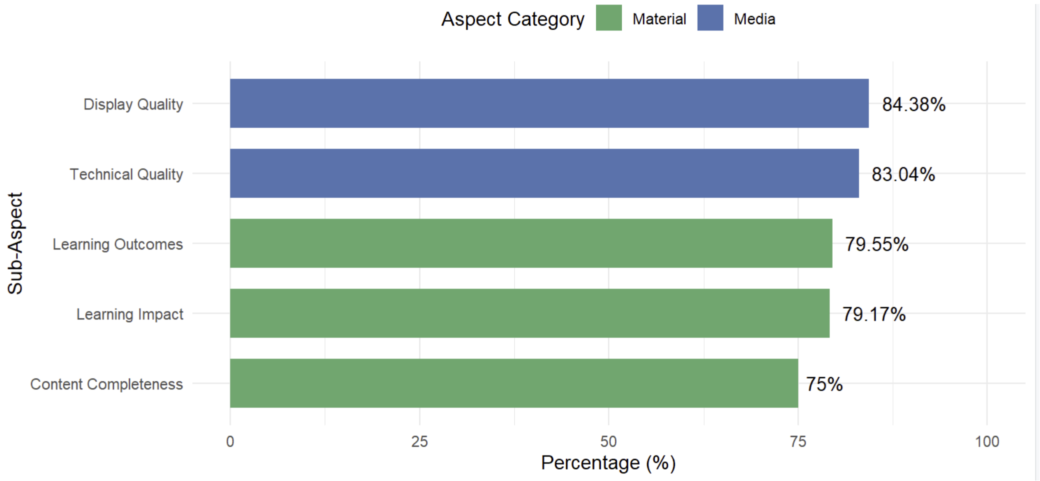

Figure 7. Comparative analysis of feasibility levels across technical and instructional aspects

In contrast, the material aspect was categorized as “feasible,” with percentage values ranging from 75.00% to 79.55%. The learning outcomes aspect achieved 79.55%, indicating that the system aligns well with the intended instructional objectives. Meanwhile, content completeness and learning impact obtained 75.00% and 79.17%, respectively. As shown in Figure 7, these values are consistently lower than those of the media aspect, indicating a relative gap between technical performance and instructional design quality. These results suggest that although the instructional component is adequate, it remains less optimized compared to the technical implementation of the system.

This discrepancy between media and material aspects highlights a key finding: the PLC Outseal system is strongly developed from an engineering perspective, with emphasis on system functionality and integration performance, while the pedagogical component, although acceptable, presents opportunities for further refinement. The visual comparison in Figure 7 reinforces this interpretation by clearly showing the dominance of technical aspects over instructional ones. This indicates that future development should focus on enhancing instructional depth, contextual learning scenarios, and alignment with higher-order learning objectives.

From an instructional standpoint, the feasibility gap can be interpreted through established learning theories. The current material primarily supports lower-order cognitive processes knowledge acquisition and procedural understanding, corresponding to the *Remember* and *Understand* levels in Bloom’s Revised Taxonomy [28]. However, the relatively lower scores in content completeness (75.00%) and learning impact (79.17%) indicate limited support for higher-order thinking. This aligns with constructivist learning theory, which emphasizes active engagement in meaningful problem-solving rather than passive content reception [29]. The current design, while technically aligned, does not yet fully incorporate contextual scenarios or guided inquiry to promote deeper cognitive engagement.

To ensure the validity of the evaluation instruments, content validity analysis was conducted using Aiken’s V coefficient, as summarized in Table 3. The media evaluation instrument achieved a coefficient of 0.852, categorized as “very high,” while the material evaluation instrument obtained a coefficient of 0.716, categorized as “high.” These results confirm that the instruments used in this study possess strong content validity and are appropriate for evaluating both technical and instructional aspects of the system.

Table 3. Content validity evaluation instruments

Instrument	Number of Items	Aiken’s V	Validity Level
Media Evaluation	18	0.852	Very High
Material Evaluation	17	0.716	High

Furthermore, inter-rater reliability analysis was conducted using Cohen’s Kappa to evaluate the consistency of expert judgments, as shown in Table 4. The results indicate that the significance values for both media experts (0.629) and material experts (0.486) are greater than 0.05, leading to the acceptance of the null hypothesis (H_0). This implies that there is no statistically significant disagreement between evaluators, confirming that the assessment results are consistent and reliable.

Table 4. Inter-rater reliability analysis

Evaluation Aspect	p-value (Sig.)	Decision ($\alpha = 0.05$)	Interpretation
Media Experts	0.629	Accept H_0	Agreement is consistent; no significant disagreement
Material Experts	0.486	Accept H_0	

From an engineering standpoint, the combined results of feasibility, validity, and reliability analyses demonstrate that the Outseal PLC system meets the required standards for implementation as a control system platform. The high feasibility scores in the media aspect confirm that the system is technically sound, with effective integration between hardware and software components, the validated and reliable evaluation instruments ensure that the assessment outcomes are robust and credible.

The findings also imply that the system has strong potential for application beyond instructional use. The high technical feasibility indicates that the Outseal PLC system can function as a product for basic automation systems, particularly in scenarios requiring simple control logic and modular input–output configurations. However, to maximize its effectiveness as a learning medium, further enhancement of instructional content and learning design is recommended.

4 Conclusion

This study presents the development and validation of a real-time control system architecture that integrates ladder-based logic with deterministic execution and cyclic scan operation. The proposed system demonstrates the capability to realize essential control functionalities, including structured input-output mapping, real-time processing, and stable hardware–software integration within a scalable and cost-efficient framework. Quantitative evaluation confirms high technical feasibility, with technical and display aspects achieving 83.04% and 84.38%, respectively (very feasible), while instructional aspects range from 75.00% to 79.55% (feasible). Content validity analysis indicates strong instrument reliability, with Aiken's V values of 0.852 (very high) and 0.716 (high), and inter-rater reliability results confirm consistent expert agreement (Sig. > 0.05).

These results validate the proposed architecture as a robust and reliable control system platform for automation applications. The identified gap between technical performance and instructional aspects suggests the need for further refinement in learning design. Future work should focus on enhancing instructional integration and conducting user-based evaluations to assess system effectiveness in real learning environments.

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