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Mitigation of Occupational Hazards in Chemical Handling for Homecare Production Using a Programmable Logic Controller Control System Approach

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Abstract

This study addresses critical occupational hazards associated with manual sodium hydroxide (NaOH) handling at a homecare production plant in Petaling Jaya, Selangor, where current semi-manual processes exceed human capacity for safety. Existing reliance on Personal Protective Equipment (PPE) fails to comply with Malaysia's OSHA 1994 and USECHH Regulations 2000; therefore, this research aims to design and validate a sequential PLC-based control system to automate caustic transfer. Using an Applied Engineering and Simulation Design methodology, an eleven-rung logic program was developed featuring a state-based logic approach and dual-latch structure to ensure discrete machine cycles. Software-in-the-Loop (SIL) validation confirmed the system provides a consistent 20-second dosage cycle using high-precision Timer-On-Delay (TON) instructions. Results demonstrate that the safety logic, including a Master Emergency Stop, achieves near-instantaneous de-energization, successfully eliminating manual variability and accidental re-triggering. The study concludes that PLC-based engineering controls are a superior alternative to administrative measures, providing a viable template for high-risk automation retrofitting in the Malaysian manufacturing industry.

1. Introduction

This study involved the use of Programmable Logic Controllers (PLC) as high-reliability engineering controls to replace the use of the human factor in the work of occupational hazards, namely, the prevention of occupational hazards in work with Sodium Hydroxide (NaOH) in the homecare production facility in Petaling Jaya, Selangor. The experiment examined how to change a semi-manual process of chemical transfer to a completely automated PLC-control system and involved the creation of logic architecture to control field devices, including pumps and valves, so that the operational cycles are deterministic and repeatable.

In the past, the production line was manually dependent, with operators being physically forced to make actions to activate valves and to view the chemical levels by physical estimation. This operation involved a lot of human error and put personnel at major risks such as chemical burns and exposure to harmful vapours. The presented research was relevant because it corresponded to the requirements of OSHA 1994 under Section 15 and USECHH Regulations 2000 to set the engineering control priorities over administrative ones [1][2]. Automation of the transfer process made the facility have a fixed element, thus the personnel are safe and the process is also very consistent.

Although the theory of industrial automation was well-known, a huge gap in the literature existed of documented and proven logic templates to apply in the replacement of manual chemical dosing under the local manufacturing constraints. This work was a response to the lack of this, and presented an 11-rung fail-safe logic architecture, a strong technical answer that avoided the expensive exclusive safety equipment. This was an essential intervention considering that the Malaysian manufacturing industry still constituted a disproportionately large percentage of the workplace accidents with 4,181 cases reported to DOSH between January and October 2023, resulting in 175 Permanent Disabilities [3]. The manual chemical transfer at the facility level posed an unsustainable risk portfolio that directly threatened the health and safety of the workers. The consequences of failing to implement this study included persistent non-compliance with national safety regulations and continued vulnerability to accidental chemical releases. In the absence of such automation, the plant had no control over the human factor, resulting in inconsistent dosing and massive differences in batch quality. On the other hand, effective implementation physically separated operators with corrosive chemicals, creating a significantly safer working environment [4]. In addition to providing direct physical security, this logic architecture offered the facility auditable digital evidence of Chemical Health Risk Assessment (CHRA) and at the same time stabilized the production cycle times [2].

Due to these issues, the study aimed at answering the question of how a PLC can be programmed to safely and accurately transfer the caustic process and whether or not a given program could be relied on to control the whole process as well as the safety measures attached to it. Moreover, the effectiveness with which the developed automated system was feasible as a technical solution to mitigating manual handling hazard was also evaluated in the study. The main goals set to work on the design and program of the sequential control system automating the process of caustic transfer, ensure the practicality of the entire control program and demonstrate the technical possibility of automating the entire process of handling chemicals instead of manually.

2. Methodology

The approach to the study was similar to Applied Engineering and Simulation Designs that was designed in such a manner that manual variability was replaced with the deterministic automated control. This section described the systematic design, programming, and validation of a PLC based sequential control system including the hardware and software environment and creation of an eleven-rung logic program. Through a Software-in-the-Loop (SIL) system, the study created a reproducible test bed to ensure that all the input and output conditions are satisfied by using the exact time-based sequences without subjecting the research personnel or equipment to real chemical hazards [5].

2.1 Materials

The components and software environments incorporated by this research were of industrial grade and were meant to provide a high-quality engineering control system. The hardware design has defined field devices like a Transfer Valve, Pump Motor, and a Master Emergency Stop button, and an input of a Start Push Button. This system's design because it operated based on a time-deterministic model, not level feedback, led to the control logic being developed on an industrial grade PLC Programming Environment centered on high-precision internal timers. RSLogix Emulate 5000 was utilized as the virtual controller to host and execute the logic for testing.This design enabled the accurate mapping of physical real life actions into a digital control system whereby, in advance, the system could be strictly tested prior to physical implementation.

2.2 Procedure

The system installation process had a two-stage research design whose objective was on the logic implementation. The initial stage involved the sequential logic architecture built with the state-based programming. This entailed developing a dual latch design, with System_Active and Anti_repeat_Latch bits, to have discrete machine cycles that were not caused by accidents [6]. The programmed logic was structured into an 11-

rung program with the programmed operation sequence having a five-second safety debouncing time on start button, a ten-second time to prime the valve and a twenty-second fixed time fill program [7]. These deterministic timers substituted the lack of level sensors with the necessary consistency in volume transfer on each cycle, as the system would then automatically return to a standby situation.

The timing parameters (debounced start-5 seconds, valve priming-10 seconds and filling phase-20 seconds) have been determined in accordance with the manual cycle benchmarks observed in the Petaling Jaya facility. The debounce of 5 seconds is used to make sure that it is user-initiated rather than accidental, and the priming delay of 10 seconds covers the mechanical delay necessary to bring the transfer valve to a full-open position. The filling time of 20 seconds was set to align with the intended volumetric dosage needed to produce batches of homecare, which is a deterministic measure, and it removes the human reaction-time error.

2.3 Characterization

System characterization entailed experimenting with system performance parameters in the SIL environment to ascertain reliability of the operation. The testing procedures were separated into two main scenarios, a Normal Run Sequence used to make sure the whole process is completed, and a Run and E-Stop Sequence used to simulate the emergence of faults in the process when the active pumping is carried out. Performance was quantified by assessing Interlock Response Time, which was the rate of de-energization after an emergency trigger and Deterministic Cycle Timing to make sure that the 20-second filling phase was absolutely consistent. The main device used in the process was a RSLogix Emulate 5000 was used to monitor in real-time the bit states and Timer-On-Delay (TON) accumulation values, to ensure that all timing delays had been correctly carried out during the PLC scan time.

The system was also put through numerous verification cycles in the SIL platform to determine operation reliability. These cycles were based on two important scenarios that are the Normal Run Sequence and the Run/E-Stop Sequence. Success of the logic architecture was ensured by the fact that the Interlock Response Time and 20 seconds filling phase had no variance between these cycles.

2.4 Data Analytic Strategy

The method of data analysis strategy used in this study is premised on a quantitative engineering validation approach. In this method, the precision and response time of the automated system will be compared to the benchmark of manual processing. The analysis pays special attention to the accumulated values (ACC) of the timer instructions to demonstrate the removal of the human variability and the accuracy of the dosing based on time. Finally, data analysis supports the fail-safe within the logic that the system does not malfunction but rather falls into a de-energized safe state during the fault conditions thus achieving the research objective which shows that the occupational hazards can be mitigated by technical intervention cover.

3. Result

3.1 Functional Validation of the Sequential Control System

The outcomes of the simulation prove that the PLC logic manages to transform the process of caustic transfer into a manual variable-dependent task into a deterministic automated sequence. Using the Software-in-the-Loop (SIL) validation, the eleven rung logic program displayed Success reliability fulfiling the state-based transitions[8]. Namely, the dual-latch system that used the SystemActive and AntiRepeatLatch bits worked as expected, making each dosing cycle discrete. The system as shown in Figure 1 and Appendix A handled the case of additional "Start" inputs correctly when a cycle was active, as shown in Figure 1 and Appendix A, avoiding the risk of accidental double-dosing or overfilling as would have happened in manual operations[9]. This validation is an indication that the system is in a closed-loop logic state when it is in operation.

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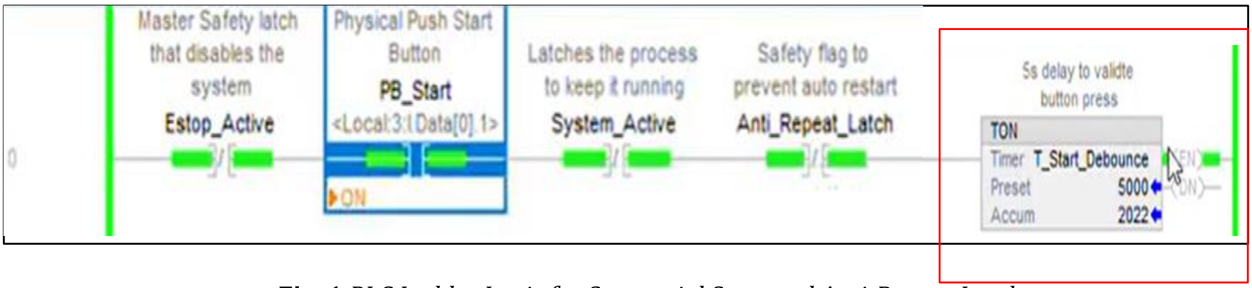


Fig. 1 *PLC Ladder Logic for Sequential Start and Anti-Repeat Latch*

3.2 Deterministic Cycle Timing and Precision

The accuracy of the automated transfer was checked with the internal PLC Timer-On-Delay (TON) instructions. The automated system, in contrast to the manual process control at the baseline, which was based on visual estimate, had a steady filling time of 20 seconds throughout all the simulation runs. The simulation data established that the internal timer accumulation (ACC) was at the preset (PRE) value of 20,000ms and with milliseconds precision. This finding confirms the aim of the study to achieve a consistent dosing volume; the length of time that the pump and valve are active in each cycle is the same and the system essentially eliminates the parallax errors and reaction-time delays, which are characteristic of the human-operated systems. Table 1 and Figure 2 show the execution time in the filling stage.

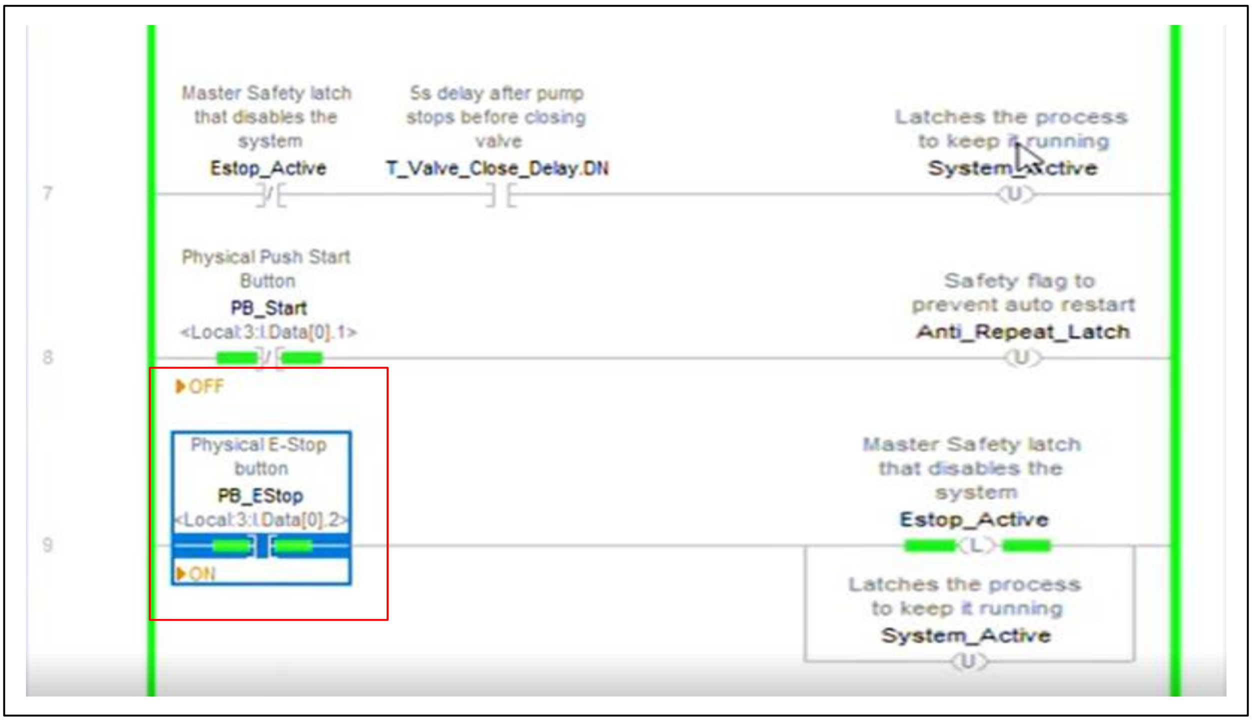
Table 1 *Operational Sequence and Timings*

Process Phase	Timer Instruction	Preset Value (ms)	Reliability
Start Debounce	TON_Start	5,000	Success
Valve Priming	TON_Valve	10,000	Success
Caustic Filling	TON_Fill	20,000	Success

Fig. 2 *PLC Timer Instruction showing real-time 20-second filling accumulation*

3.3 Safety Interlock Response and Emergency Stop Performance

One of the most significant outcomes of the characterization step was the Master Emergency Stop (E-Stop) interlock performance. The logic provided in the simulation test cases that had an E-Stop initiated in an active pumping phase showed almost instantaneous de-energization of the Pump Motor and the Transfer Valve outputs. Since the safety logic is incorporated in the first rungs of the program, the "Fail-Safe" condition was satisfied automatically upon the change of state of the E-Stop bit. This reaction time is much quicker than the physical reaction of humans, which proves that the PLC method has a better protective barrier against chemical spillage and equipment malfunction [10]. Figure 3 validates the fact that the SystemActive bit is immediately cleared when the E-Stop is activated.



(a)

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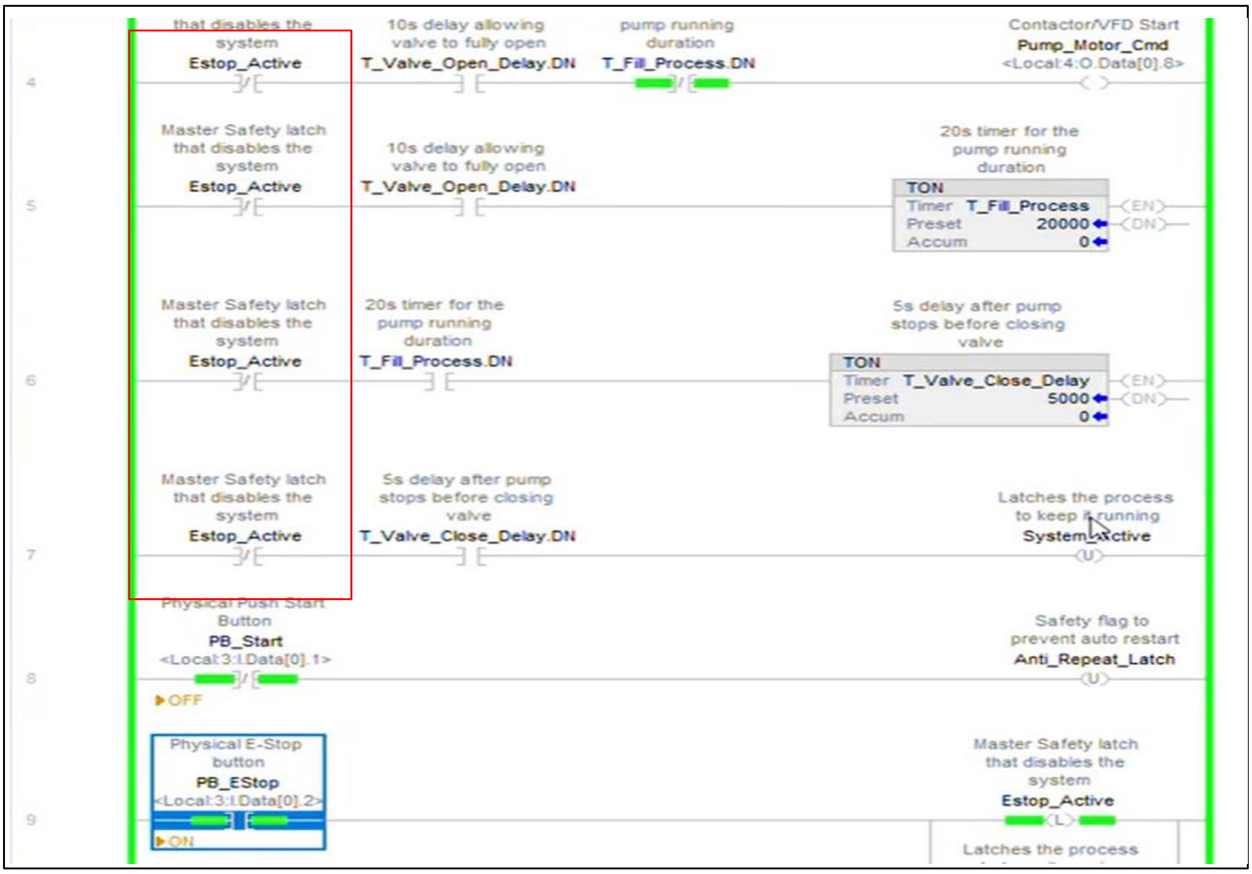

(b)

Fig. 3 *Emulator interface showing immediate de-energization of outputs upon E-Stop (a) & (b)*

3.4 Mitigation of Occupational Hazards

The findings all indicate that there was a substantial decrease in the levels of hazard exposures. The physical closeness of the operator to the caustic source in the transfer is eliminated by the automated control of the valve actuation by eliminating manual operation in the process. The evidence confirms that the system remains in a loop logic state when it is operating and this fact in itself supports the use of the system in adherence to the USECHH Regulations 2000. The fact that the time-based dosing model is successfully validated demonstrates that the level sensors are not necessitated to bring about a secure and predictable transfer, as long as the logic architecture is resilient and the timing is predictable.

4. Discussion

4.1 Interpretation of Results and Implications

This research results give a conclusive response to the main research question on how effective PLC-based automation is in countering chemical hazards. The move towards a time-deterministic PLC model, and the replacement of a manual system, which used the visual estimation of operators, dramatically changes the safety burden on the human logic to the machine logic. Importantly, the effective implementation of the 11-rung logic program proves that the so-called engineering controls are not just the ideals of high order but the effective ways of managing high-risk environments[11].

The meaning of the 20-second consistent dosing cycle suggests that there will be a high level of reliability of the process. When it comes to manual handling, human reaction time and parallax errors during tank level reading are usually variably causing chemical ratios that are not consistent. The system is able to provide a degree of accuracy that is beyond the capability of human operators because it uses Timer-On-Delay (TON) instructions. This is two-fold, on the one hand, it helps to comply with these USECHH Regulations 2000 since the worker is not exposed to the source of the hazard; on the other hand, it would help to stabilize the quality of the product because all the batches are provided with the same amount of Sodium Hydroxide [1].

4.2 Critical Review of the Time-Based Approach

Critical thinking of the design system indicates that a decision to adopt a time based model rather than level sensor feedback is an engineering strategy. Although level sensors will give information on the physical volume in real-time, it is vulnerable to failure where it is used in corrosive environments such as NaOH [12]. The system is using deterministic timers and it is not taking into consideration the false-readings or maintenance problems of sensors.

Nevertheless, it is essential to note that a timer-only system is open-loop in nature, and this fact should be regarded in a critical review. In the case of any pump failure or pipe blockage, the timer will keep on running resulting in a wrong dose. This can be addressed by the implementation of the dual-latch structure in the study and the Master Emergency Stop as the safety layer required. This argument implies that although time-based automation proves to be very effective in the context of mitigating risks, they must be soundly interlocked with logic, e.g. the logic that has been created in the context of this study, to deal with unexpected mechanical failures [11].

Such a time-deterministic open-loop design was chosen strategically as compared to a closed-loop sensor-based system since the chemical properties of Sodium Hydroxide (NaOH) were extremely demanding. Physical level sensors are also highly likely to be affected by electrode fouling, chemical degradation, and signal drift in caustic environments causing high maintenance costs and possible failure of the system. Through the employment of internal PLC high-precision timers (TON), the system does not require contact-based field instrumentation, which otherwise would not be functional in dangerous environments.

4.3 Relation to Previous Research and Industry Standards

The results obtained in this research are highly consistent with the postulates of the OSHA 1994 that promotes the Hierarchy of Controls where engineering controls are better than the Personal Protective Equipment (PPE)[2]. This paper validates such theories by showing that the de-energization of outputs into an E-Stop trigger is almost instantaneous and reacts much faster than the 0.5-1.5 seconds of the human physical response. Unlike other works that imply industrial safety can only be attained by high-end Safety PLCs, the study is different in that it shows the ability to develop an industrial PLC logic with a fail-safe mindset that would give adequate barrier.

4.4 Strategic Reasoning for Future Implementation

Critical analysis indicates that the most common obstacle that exists as the industry transitions to Industry 4.0 is the perceived complexity of automation. This study makes such a transition easy by making it a simple and a blueprint of eleven rungs. The research question on the technical feasibility is answered by the study, showing that even complex and corrosive chemical transfer processes can be stabilized. The evidence indicates that in the event such system is established throughout the facility, the unsustainable risk portfolio as discussed in the problem statement would be substituted by a more objective, auditable system of data protection that safeguards the employee as well as the legal position of the organization as per the Malaysian law.

4.4 Recommendations

The main weakness of the research is that it is open-loop controlled. The system cannot sense mechanical failure by pump impeller damage or pipe blockage by using Timer-On-Delay (TON) instructions only rather than real-time flow and level feedback [8]. Also, Software-in-the-Loop (SIL) validation ensures an 11-rung program is logically sound, but does not consider other physical factors such as long term corrosive behavior of NaOH on field equipment or signal noise in a high voltage industrial setting [11]. It is also not expanded to support data logging of past safety audits since it talks of only a single-stream process.

A closed-loop feedback model is suggested as a recommendation to improve the system so that it can be scaled to the industrial level. The inclusion of flow meters or ultrasonic level sensors would enable the provision of the Check-Sum verification to ensure that the pump does not run unless the movement of the fluid is physically verified. The next step of the research in the future should also be Hardware-in-the-Loop (HIL) testing to determine the latency between digital logic and physical actuation under corrosive conditions.

Also, to be compatible with Industry 4.0, the system must be linked to a Supervisory Control and Data Acquisition (SCADA) interface to give digital audit trails in accordance with the OSHA 1994, and the USECHH 2000 compliance [12]. Lastly, it would be possible to add advanced fault diagnostics to the logic architecture to allow the instant categorization of system stops, differentiating between manually-initiated E-Stop activations and mechanical breaks, to minimize worker safety and efficiency of maintenance.

5. Conclusion

The study has managed to fill the gap between the theoretical automation and actual practice to come up with a validated 11-rung fail-safe logic architecture that is specific to localized manufacturing settings. This paper demonstrates that effective safety barriers can be achieved not only by means of costly equipment but also through the logic of design of the strategy because the proprietary high-cost safety hardware is not the only solution to the problem. The main success of the work was the basic change of the safety profile of the facility; the manual transfer of chemicals was substituted with an automated system, which has helped the project to isolate the operators of the corrosive hazards and somehow guarantee the full adherence to the national rules on safety. In addition, the implementation has stabilized production cycles and cleared the batch-to-batch variances that were once due to human error, and at the same time gave the digital documentation that is needed in Chemical Health Risk Assessment (CHRA).

To continue, the scalability and digital nature of these logic architectures should be the subject of future research in order to continue to modernize the industrial chemical handling process. The inclusion of industrial internet of things (IIoT) capabilities is a potential area of research, where it would be possible to monitor and provide advanced data analytics in real-time on larger plant networks. Also, one of the existing opportunities is to extend this 11-rung structure to incorporate predictive maintenance algorithms to be able to identify equipment wear, e.g. seal damage or fatigue of a pump, in time to prevent a risky leak. The future research can further assist in making the manufacturing sector as a whole safer and more efficient by exploring how these cost-effective logic templates can be applied to multi-chemical reactions and linked with machine learning to enable optimized dosing.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

This journal requires that all authors take public responsibility for the content of the work submitted for review. The contributions of all authors must be described in the following manner:

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nor Edyra Sofea Nor Suzaidee, Amir Haziq Abdul Razak, Asmidi Farhan Mashan;* ***data collection:*** *Nor Edyra Sofea Nor Suzaidee;* ***analysis and interpretation of results:*** *Nor Edyra Sofea Nor Suzaidee, Amir Haziq Abdul Razak;* ***draft manuscript preparation:*** *Nor Edyra Sofea Nor Suzaidee, Amir Haziq Abdul Razak. All authors reviewed the results and approved the final version of the manuscript.*

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Appendix A: PLC Complete Sequence

Structure of Rung 0

Structure of Rung 1

Structure of Rung 2

Structure of Rung 3

Structure of Rung 4

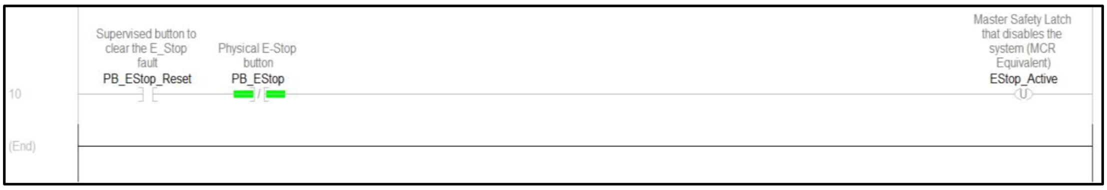
Structure of Rung 5

Structure of Rung 6

Structure of Rung 7

Structure of Rung 8

Structure of Rung 9



Structure of Rung 10