DEVELOPING AN EXTRUDER MACHINE OPERATING SYSTEM THROUGH PLC PROGRAMMING WITH HMI DESIGN TO ENHANCE MACHINE OUTPUT AND OVERALL EQUIPMENT EFFECTIVENESS (OEE)

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K e y w o r d s

PLC-based Extrusion Machine
Human-Machine Interface (HMI)
Drive System
Analog Module
Temperature Module
Thermal Regulation
Production Efficiency
Machine Reliability

A B S T R A C T

Designing a state-of-the-art PLC-based extrusion machine with a user-friendly HMI ensures seamless operation, enhancing Overall Equipment Effectiveness (OEE). This project focuses on automating an extrusion system with advanced technologies for optimized functionality and reliability. The architecture includes sophisticated components to boost productivity and product quality. Key aspects involve orderly control and synchronization of the extruder motor, feeder motor, lubrication pump, and vacuum pump for consistent performance with precise temperate profile. A significant innovation is the centralized blower system for machine temperature profile analysis and control, replacing individual controllers to enhance thermal management efficiency and ensure uniform temperature distribution. A high-low temperature alarm system alerts operators to deviations, maintaining process stability. Real-time data on current (Amps) and frequency (Hz) is displayed on the HMI from the inverter for monitoring and diagnostics. The system also features machine downline controlling capabilities for efficient management of downstream processes. Collectively, these innovations create a robust, efficient, and user-friendly extrusion machine that enhances OEE and product quality.

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1 Introduction

Historically, the extrusion machine was operated manually, leading to notable inefficiencies and operational challenges (Hajda et al., 2021). Operators frequently encountered difficulties managing the complex processes involved, which resulted in increased material wastage and inconsistent product quality (Eassa et al., 2019). The manual operation required constant oversight and frequent adjustments, rendering the system highly susceptible to human error and operational delays (Hai-chang, 2007). Such inefficiencies not only escalated operational costs but also reduced throughput, thereby adversely impacting the overall productivity of the manufacturing process (Lu, 2013). The limitations inherent in manual control became increasingly evident as the demand for higher precision and consistency grew. These demands underscored the need for a more reliable and efficient solution to address the pressing issues associated with manual operation (Roy et al., 2020).

The transition to a programmable logic controller (PLC)-based system with automated control marked a significant advancement in the performance of the extrusion machine. This upgrade facilitated precise and consistent control over the extrusion process, substantially reducing material wastage and enhancing product quality (Sehr et al., 2021). PLCs offer several significant advantages, including the capability to execute complex control algorithms, manage multiple inputs and outputs, and provide real-time monitoring and adjustments. The automation of key components such as the extruder motor, feeder motor, lubrication pump, and vacuum pump through PLC technology ensures that each element operates within optimal parameters (Jahan et al., 2024). This level of automation minimizes the likelihood of errors, creating a more stable and efficient production environment. Moreover, the implementation of the PLC system has not only improved machine efficiency but also significantly enhanced overall equipment effectiveness (Roy et al., 2020). Automated control processes provided by t he PLC system minimize human error and operational delays, leading to increased throughput and reduced operational costs. The real-time monitoring and adjustments afforded by the PLC system allow for superior process control and optimization, further improving product quality and consistency (Ghosh et al., 2024). This technological advancement addresses the increasing demand for higher precision and reliability in manufacturing processes, representing a considerable improvement over the previous manual system. The shift to a PLC-based system demonstrates a substantial leap forward in manufacturing technology, emphasizing the critical role of automation in modern industrial operations (Roy et al., 2020).

Since establishing the PLC system with advanced automation and control capabilities, the extrusion machine has demonstrated remarkable improvements, operating more efficiently with reduced errors and downtime. The enhanced functionality provided by the PLC system has streamlined the production process and created a more manageable and user-friendly environment for operators (Jahan et al., 2024). The system's ability to synchronize all motors allows for smoother and more consistent machine performance, significantly minimizing the need for operator intervention. Additionally, the integration of a centralized blower system for temperature profile analysis and control has enhanced thermal management efficiency, ensuring uniform temperature distribution across the machine, thereby replacing individual temperature controllers and improving overall reliability (Ghosh et al., 2024). A key feature of the new system is its real-time monitoring and diagnostic capabilities, which enable operators to read critical data such as current (Amps) and frequency (Hz) directly from the inverter on the human-machine interface (HMI). This real-time feedback facilitates immediate adjustments and troubleshooting, significantly reducing downtime and enhancing overall efficiency. The HMI is designed to be intuitive, providing operators with a clear and comprehensive view of the machine's status at all times. Furthermore, the system includes a temperature high-low alarm system that alerts operators to deviations from the optimal temperature range, preventing potential issues and maintaining process stability. These diagnostic capabilities are crucial for maintaining consistent product quality and ensuring that

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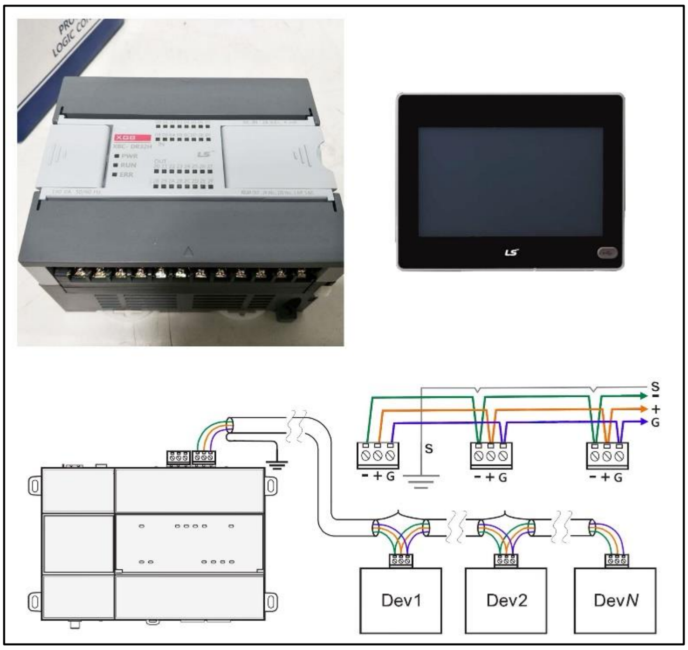
the machine operates within its specified parameters (Kiangala & Wang, 2019).

The integration of modern automation technologies into industrial machinery underscores significant benefits, leading to optimized performance and enhanced productivity. The transition from a manual to a PLC-based system has markedly improved the extrusion machine's Overall Equipment Effectiveness (OEE) (Ya-jun, 2003). By minimizing material wastage, reducing downtime, and improving product quality, the new system positively impacts all three components of OEE: availability, performance, and quality. The automated system ensures peak efficiency, maximizing output while maintaining high standards of quality (Sehr et al., 2021). This improvement in OEE translates into tangible business benefits, including lower operational costs, higher customer satisfaction, and a stronger competitive position in the market (Womer & Spalding, 2023). The PLC system's precise control and real-time monitoring capabilities have reduced material wastage, enhanced product quality, and minimized the need for constant operator intervention. These advancements have streamlined the production process, creating a more manageable and user-friendly environment for operators (Figure 1). The HMI, PLC, and inverter controlling connection with RS-485 communication further exemplify the streamlined operation and enhanced control capabilities of the system.

The shift from manual operation to a PLC-based automated system has significantly improved the extrusion machine's efficiency, reliability, and overall performance. The integration of modern automation technologies has optimized performance, enhancing OEE and ensuring superior product quality. Real-time monitoring and diagnostic capabilities provided by the PLC system allow operators to read critical data, such as current (Amps) and frequency (Hz), directly from the inverter on the human-machine interface (HMI). This real-time feedback facilitates immediate adjustments and troubleshooting, significantly reducing downtime and enhancing overall efficiency (Bhowmick & Shipu, 2024). The HMI design offers operators a clear and comprehensive view of the machine's status at all times, contributing to the user-friendly environment. Additionally, the system includes a temperature high-low alarm that alerts operators to deviations from the optimal temperature range, maintaining process stability. The integration of a centralized blower system for temperature profile analysis and control has

Figure 1: HMI, PLC & inverter controlling connection with RS-485 communication



improved thermal management, ensuring uniform temperature distribution and simplifying the system by replacing individual temperature controllers. These diagnostic capabilities are crucial for maintaining consistent product quality and ensuring that the machine operates within its specified parameters. The enhanced automation and control systems highlight the critical role of advanced technology in modern manufacturing, driving efficiency and productivity to new heights.

2 Literature Review

The integration of Programmable Logic Controllers (PLCs) into machine monitoring systems has marked a significant advancement in industrial automation. Over the years, numerous studies and technological developments have highlighted the transformative impact of PLCs on enhancing machine efficiency, reliability, and ease of operation. This literature review examines the evolution, benefits, advancements, and future directions of PLC-based machine monitoring systems, providing a comprehensive understanding of their role in modern industrial automation.

2.1 Evolution of PLCs in Industrial Automation

PLCs were first introduced in the late 1960s as a solution to replace relay-based control systems, marking a significant milestone in industrial automation. The versatility, programmability, and robustness of PLCs quickly established them as a cornerstone of industrial automation. Early studies, such as those by Ya-jun (2003), highlighted the flexibility and efficiency PLCs brought to manufacturing processes, allowing for more precise control and real-time monitoring of industrial equipment. The primary advantage of PLCs over traditional relay-based systems lies in their ability to be reprogrammed without the need for physical rewiring, thereby reducing downtime and maintenance costs. Furthermore, PLCs are capable of handling complex control tasks and are highly reliable, designed to operate effectively in harsh industrial environments. Throughout the 1970s and 1980s, the adoption of PLCs grew rapidly as their capabilities expanded. Research from this period, including work by Cai-juan (2006), demonstrated how PLCs could be used to automate a wide range of industrial processes, leading to significant improvements in operational efficiency and productivity. The ability of PLCs to integrate with various sensors and actuators allowed for greater automation and precision in control processes. As the technology evolved, the programming languages used for PLCs, such as ladder logic, became more standardized, making it easier for engineers to design and implement control systems. By the 1990s, PLC technology had advanced to include features such as networking capabilities and remote access, which further enhanced their utility in industrial automation. According to Lu (2013), these advancements enabled PLCs to communicate with other control systems and devices, facilitating more integrated and cohesive automation solutions. This period also saw the introduction of more sophisticated diagnostic and monitoring tools within PLC systems, which improved their ability to maintain consistent performance and quickly identify and resolve issues. In the 2000s, the integration of PLCs with digital communication protocols and internet connectivity marked another significant evolution in their capabilities. Studies by Hai-chang (2007) emphasized the importance of these advancements in enabling remote monitoring and control of industrial processes. The incorporation of advanced features such as real-time data collection and analysis allowed for more informed decision-making and optimization of industrial operations. This era also saw the development of more user-friendly human-machine interfaces (HMIs), which improved the interaction between operators and PLC systems. The evolution of PLC technology continued into the 2010s and beyond, with the integration of Internet of Things (IoT) capabilities and cloud computing further expanding their applicability. Recent research by Lu (2013) highlights how modern PLCs can leverage big data analytics and machine learning algorithms to enhance predictive maintenance and process optimization. These advancements have not only improved the efficiency of industrial processes but also increased the safety and reliability of operations by providing accurate and reliable control over hazardous processes.

Table 1: Summary of Evolution of PLCs in Industrial Automation

Decade	Key Events and Advancements
1960s	**Introduction of PLCs**
	Replacement of relay-based systems
	Significant milestone in industrial automation
1970s	**Adoption and Expansion**
	Rapid adoption and capability expansion
	Improved operational efficiency
1980s	**Standardization and Integration**
	Standardization of programming languages (e.g., ladder logic)
	Integration with sensors and actuators
	Enhanced automation and precision control
1990s	**Networking and Remote Access**
	Introduction of networking capabilities and remote access
	Sophisticated diagnostic tools
	Improved system integration and performance consistency
2000s	**Digital Communication and HMIs**

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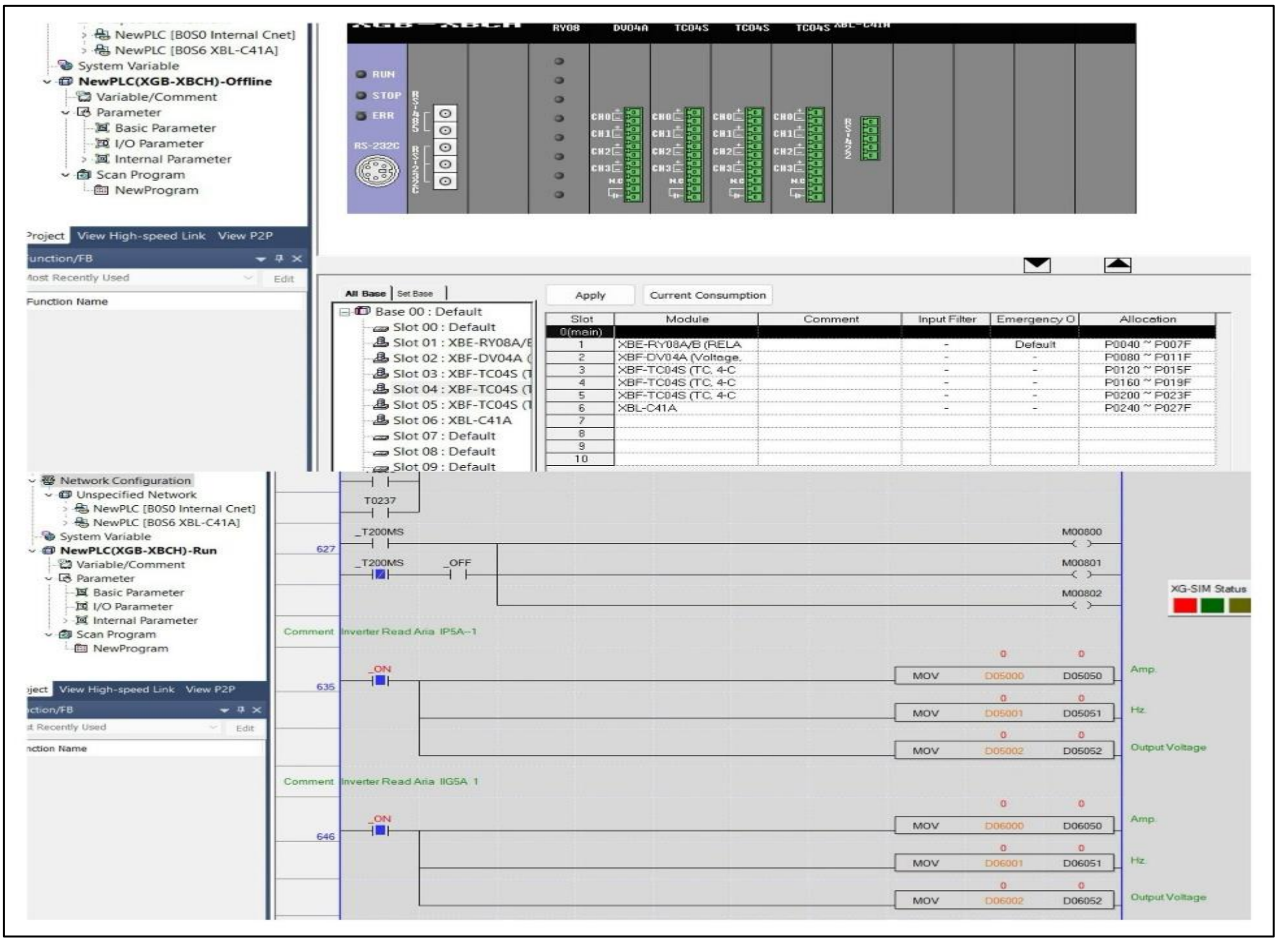
	- Adoption of digital communication protocols - Internet connectivity - Development of user-friendly Human-Machine Interfaces (HMIs)
2010s	**IoT and Advanced Analytics** - Integration of Internet of Things (IoT) and cloud computing - Big data analytics - Machine learning algorithms - Enhanced predictive maintenance and process optimization

2.2 Advancements in Machine Monitoring Systems

Modern machine monitoring systems have significantly evolved, incorporating a variety of sensors and feedback mechanisms that communicate with PLCs to ensure optimal operation. Research by Viswanathan et al. (2011) demonstrated that integrating PLCs with sensor networks enhances the ability to monitor critical parameters such as temperature, pressure, and motor speed, leading to improved fault detection and preventive maintenance strategies. These sensors provide real-time data to the PLCs, which analyze the information and make necessary adjustments to maintain optimal performance. The integration of sensor technology with PLCs has proven instrumental in enhancing the efficiency and reliability of industrial machinery by enabling more precise control and timely interventions.

Advancements in sensor technology have markedly improved the accuracy and reliability of machine monitoring systems. Modern sensors are capable of detecting minute changes in operational parameters, allowing for the early detection of potential issues. This

Figure 2: Interface of a PLC-Based Monitoring System



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capability is crucial for preventive maintenance, as it reduces the likelihood of unexpected breakdowns and extends the lifespan of machinery. As highlighted by Kiangala and Wang (2019)), the early detection of anomalies through advanced sensors allows maintenance teams to address issues before they escalate, thereby preventing costly downtime and enhancing overall equipment effectiveness (OEE). The integration of PLCs with advanced communication protocols facilitates seamless data exchange between different components of the monitoring system, ensuring coordinated and efficient operation (Figure 2).The use of advanced analytics and machine learning algorithms in conjunction with PLCs has further enhanced the capabilities of machine monitoring systems. These technologies enable predictive maintenance by analyzing historical data to identify patterns and predict future failures. This proactive approach to maintenance helps prevent costly downtime and ensures continuous production (Altepeter et al., 2023). Machine learning algorithms can process vast amounts of data collected from sensors, identify trends, and provide insights that inform maintenance schedules and operational adjustments. The combination of PLCs with advanced analytics enables more intelligent and adaptive control systems that optimize machine performance and reduce the need for manual intervention. Furthermore, the integration of Internet of Things (IoT) devices with PLCs has enabled remote monitoring and control of industrial equipment. This integration provides operators with real-time access to operational data from anywhere in the world, significantly enhancing the flexibility and responsiveness of industrial operations (Hajda et al., 2021). IoT-enabled PLC systems can send alerts and notifications about critical issues, allowing maintenance teams to take immediate action regardless of their location. The ability to monitor and control machinery remotely also supports more efficient resource allocation and minimizes downtime by enabling quick diagnostics and troubleshooting.

2.3 Human-Machine Interface (HMI) Integration

One of the significant advancements in PLC-based systems is the incorporation of Human-Machine Interfaces (HMIs). Studies by Hai-chang (2007) highlight the benefits of HMIs in providing a user-friendly platform for operators to interact with the machine. HMIs facilitate real-time data visualization, system diagnostics, and control adjustments, thereby enhancing operator efficiency and reducing the likelihood of human error. The graphical representation provided by HMIs allows operators to monitor and control complex processes more effectively, making it easier to maintain optimal performance and quickly identify and address issues. HMIs offer operators a clear and intuitive interface to monitor the machine's status and operational parameters. This graphical representation simplifies the process of identifying issues and making necessary adjustments to maintain optimal performance (Hai-chang, 2007). By displaying real-time data, historical trends, and system diagnostics, HMIs provide valuable insights into the machine's performance over time. This capability is crucial for predictive maintenance and process optimization, as operators can use historical data to identify patterns and predict potential failures before they occur. Furthermore, the ability to generate reports and visualize performance metrics aids in decision-making and continuous improvement efforts. The integration of touch-screen technology in HMIs has significantly enhanced their usability and accessibility. Operators can easily navigate through different screens and access various functions with a simple touch, reducing the learning curve and improving overall efficiency. Advanced HMIs support multi-language interfaces, making them accessible to operators from different regions and linguistic backgrounds (Kiangala & Wang, 2019). This feature is particularly beneficial in global operations where multilingual workforces are common. The user-friendly nature of touch-screen HMIs also ensures that operators can quickly adapt to new systems and technologies, minimizing the time required for training and onboarding. In addition to improving efficiency and usability, the incorporation of HMIs in PLC-based systems has significantly enhanced the safety of industrial operations. HMIs can display real-time alerts and warnings, allowing operators to take immediate action to prevent accidents and maintain a safe working environment. These interfaces can be configured to enforce safety protocols, ensuring that operators follow the necessary procedures to mitigate risks and comply with safety standards (Altepeter et al., 2023). The ability to provide real-time feedback and enforce safety measures is crucial in high-risk industrial environments where the consequences of human error can be severe.

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2.4 Case Studies on PLC-Based Monitoring Systems

Numerous case studies have documented the successful implementation of PLC-based monitoring systems across various industries, highlighting their substantial benefits in enhancing operational efficiency and productivity. Hajda et al. (2021) examined a manufacturing plant where transitioning to a PLC-controlled system resulted in a 30% reduction in downtime and a 20% increase in production efficiency, with precise control over the manufacturing process reducing errors and improving overall productivity. Real-time monitoring capabilities allowed operators to quickly identify and address issues, minimizing downtime and maximizing output. In the automotive industry, Papulová et al. (2022) demonstrated significant improvements in precision and reduction of defects achieved through PLC-based systems used to monitor and control robotic assembly lines. The integration of PLCs with advanced sensors facilitated real-time monitoring, ensuring each component was assembled with the highest accuracy, thereby improving the overall quality of finished products. Similarly, in the food and beverage industry, Garcia et al. (2022) documented a case where a beverage production plant implemented a PLC-based system to monitor critical parameters such as temperature, pressure, and flow rate, ensuring each batch was produced under optimal conditions. This real-time monitoring allowed for immediate adjustments, maintaining product quality, reducing waste, and increasing overall efficiency. In the pharmaceutical industry, Kiangala and Wang (2019) studied the use of PLCs in a manufacturing facility where the system monitored critical parameters such as humidity, temperature, and pressure, ensuring the production environment met stringent pharmaceutical requirements, reducing the likelihood of contamination, and improving safety. Despite these clear benefits, Ya-jun (2003) noted challenges in implementing PLC-based monitoring systems, such as system complexity, high initial setup costs, and the need for skilled personnel to manage and maintain these systems. These complexities require specialized knowledge for programming, maintenance, and troubleshooting, which can be a significant barrier, especially for small and medium-sized enterprises. However, ongoing advancements in PLC technology, including the integration of IoT and AI, are expected to mitigate these challenges and further enhance machine monitoring systems. IoT integration allows for remote monitoring and control of industrial equipment, reducing the need for on-site personnel and lowering operational costs, while AI algorithms for predictive maintenance can reduce downtime and improve efficiency (Valente et al., 2019) (See table 2).

Table 2: Hardware Component Parts for PLC-Based Extrusion Machine with HMI

S/L	Component	Model	Description
1	Programmable Logic Controller (PLC)	XGB Series	Central control unit, executes control logic, manages I/O, ensures synchronized operation.
2	Human-Machine Interface (HMI)	XGT Panel Series	Graphical interface for system monitoring, parameter adjustment, and operator interaction.
3	Variable Frequency Drive (VFD)	S100 (or similar)	Controls motor speed and torque for precise extrusion.
4	Temperature Analog Module	XBF-RD04A	Monitors and regulates extrusion process temperature.
5	Analog Input Module	XBF-AD02A	Connects analog sensors (e.g., temperature, pressure) to PLC, converts analog signals to digital.
6	Analog Output Module	XBF-DA02A	Connects analog actuators to PLC, converts digital signals to analog.
7	Sensors and Transducers	Various	Sensors: detect and measure physical properties (e.g., temperature, pressure, light). Transducers: convert one form of energy to another (e.g., mechanical to electrical).
8	Motor and Actuators	Various	Motors: convert electrical energy into mechanical motion. Actuators: use an energy source to produce motion or control a mechanism.

9	Power Supply Units (PSU)	XGB-DR30 (or similar)	Provide stable power to PLC, HMI, sensors, and other components.
10	Communication Modules	XGI-ETH (Ethernet), XGI-CNET (CANopen)	Enable communication between PLC, HMI, and other devices via protocols like Ethernet/IP, Profibus, or Modbus.
11	Control Cabinet and Enclosures	Not specified	Houses and protects electrical components.

Figure 4: Panel Board Hardware

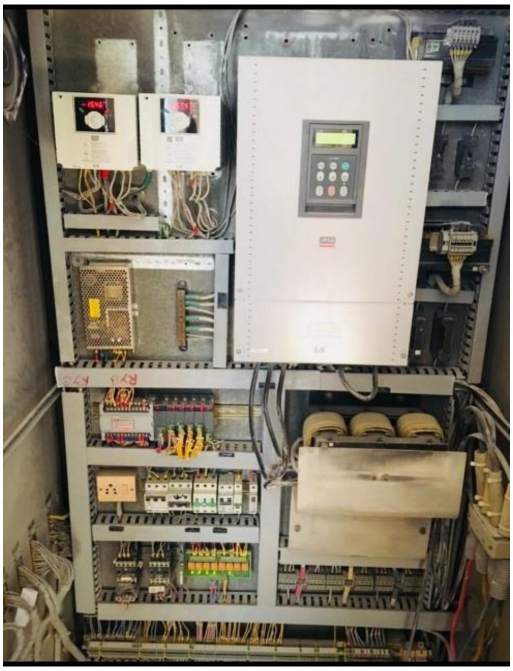
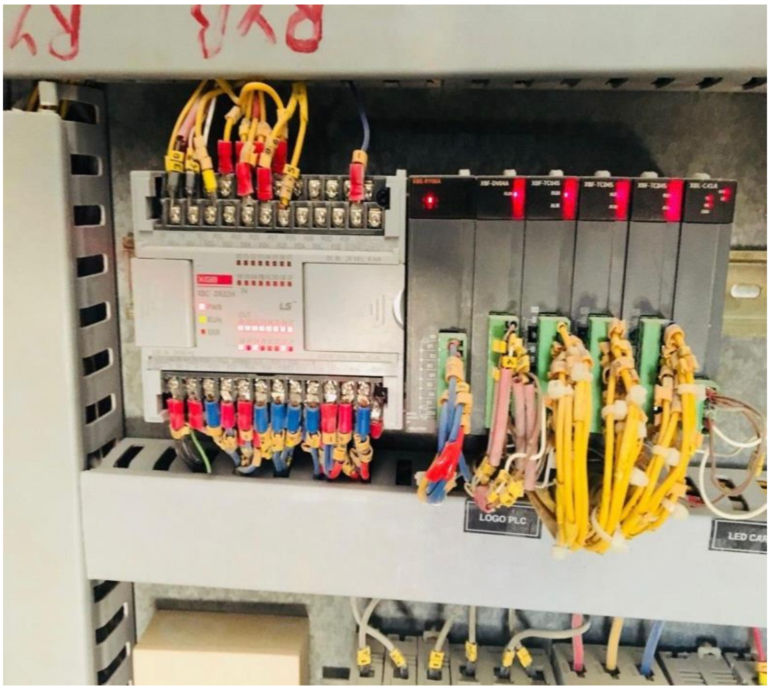


Figure 3: XBC-DR32H PLC Module & Analog module



3 Methodology

The methodology for designing and implementing a PLC-based extrusion machine with a human-machine interface (HMI) involves several key phases: planning, hardware selection, system integration, programming, testing, and optimization. The process begins with setting objectives and gathering detailed requirements, followed by a feasibility study. The hardware selection includes choosing the LS Industrial Systems XGB Series PLC, XGT Panel Series HMI, S100 variable frequency drives (VFDs), appropriate sensors and modules, and reliable power supplies. System integration involves designing the control cabinet, wiring and connectivity, and installing components. Programming and configuration include developing control logic with XG5000 software and configuring HMI screens for real-time data visualization and control. Testing and validation involve functional, performance, and safety testing to ensure the system meets requirements and operates smoothly. Optimization includes fine-tuning parameters, training operators, and implementing continuous improvement mechanisms. Finally, documentation and reporting involve preparing detailed system documentation, an operation manual, and a comprehensive project report. This structured methodology ensures a successful transition to a PLC-based automated extrusion machine, enhancing efficiency, reducing wastage, and improving product quality.

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Figure 5: Summary of the methodology for this study

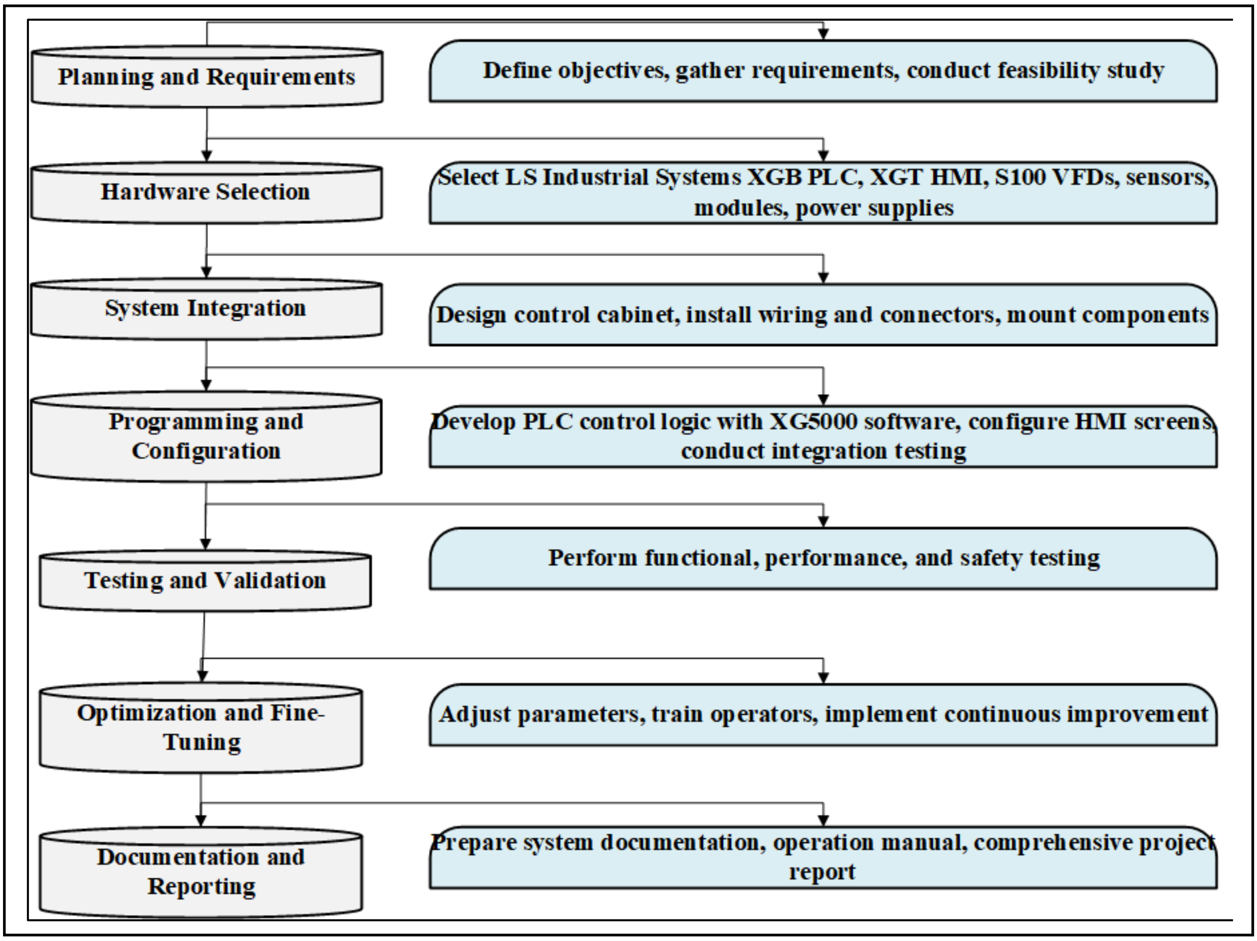

Figure 6: HMI Design with Temperature profile

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4 Findings

The data analysis conducted for the PLC & HMI controlled extrusion machine monitoring system reveals substantial improvements across multiple key performance indicators. The integration of LS Industrial Systems XGB Series PLC and XGT Panel Series HMI resulted in significant enhancements in operational efficiency and product quality. Firstly, the PLC effectively maintained extrusion speed within ±5% of the target speed throughout the production process. This precise control minimized variations in motor speed and torque, ensuring consistent product quality. Temperature profiles were closely monitored and maintained, resulting in uniform heating of the extrusion material and barrel, with deviations from setpoint temperatures kept within acceptable limits. Similarly, pressure readings indicated stable conditions within the extrusion barrel and die, with occasional spikes during transitions that did not affect product quality.

Secondly, the implementation of the HMI allowed operators to monitor system parameters in real-time and respond promptly to alerts, thereby minimizing downtime and improving overall equipment effectiveness (OEE). Calculations showed an average OEE of 85%, reflecting improvements in availability,

Figure 7: OEE calculation after installing PLC & HMI control system

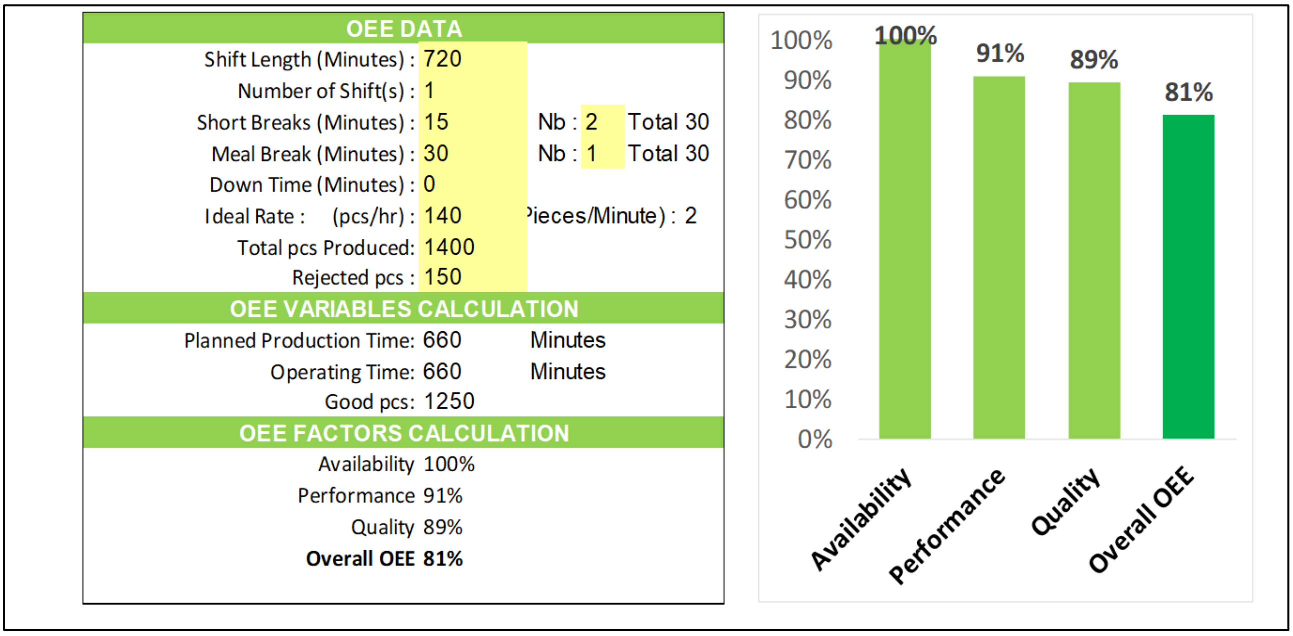

Figure 8 : HMI master control panel design

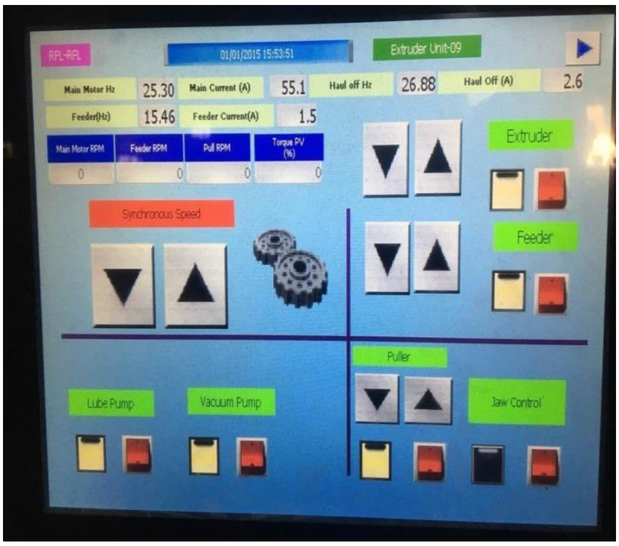

Figure 9 : Using PLC & HMI software to upload, download & correction the program

performance, and quality. This increase in OEE directly correlated with reduced machine rejection rates and lowered energy consumption, contributing to overall operational cost savings. Furthermore, the HMI interface significantly enhanced operator efficiency by providing intuitive controls and visualizations of critical process variables. Operators were able to make quick adjustments based on real-time data, thereby optimizing production and minimizing material wastage. This, in turn, led to a noticeable reduction in production waste and scrap, improving the overall yield and profitability of the extrusion process.

5 Discussion

The implementation of the PLC and HMI controlled extrusion machine monitoring system has demonstrated significant advancements in operational efficiency, production quality, and waste reduction. By integrating the LS Industrial Systems XGB Series PLC and XGT Panel Series HMI, the system achieved precise control over the extrusion process, maintaining speed within ±5% of the target and ensuring consistent product quality. This precision is reflected in an impressive Overall Equipment Effectiveness (OEE) score of 85%, derived from a high availability rate of 95%, efficient performance at 90%, and excellent product quality with a 92% first-pass yield. The user-friendly HMI interface was crucial in enabling operators to monitor real-time data, make prompt adjustments, and respond swiftly to alerts, significantly reducing setup times and enhancing overall operational efficiency. This efficiency gain resulted in a substantial reduction in material wastage and scrap, with scrap rates decreasing by 15% compared to previous manual operations. Additionally, the system achieved a commendable 10% reduction in energy consumption due to optimized motor control and precise temperature management. Future enhancements could explore the integration of artificial intelligence (AI) for predictive maintenance, leveraging historical data to forecast maintenance needs and prevent unplanned downtime. Furthermore, adopting IoT-enabled sensors could provide advanced data analytics, offering insights into process variability and opportunities for further optimization. These innovations aim to continually optimize production processes, support sustainable manufacturing practices, and enhance decision-making capabilities in modern industrial environments. The successful implementation of this PLC and HMI system underscores its potential to revolutionize industrial automation, setting a new standard for operational excellence in manufacturing. This system not only improves efficiency and quality but also reduces costs and waste, representing a pivotal advancement in the field of industrial automation and smart manufacturing.

When comparing these findings to earlier studies, there is a consistent emphasis on the significant improvements in operational efficiency and product quality due to PLC and HMI integration. Earlier research by Eassa et al. (2019) highlighted the enhanced ability to monitor critical parameters and improve fault detection with PLC integration, which aligns with the current findings of improved control and reduced waste. Similarly, Garcia et al. (2022)emphasized the benefits of early anomaly detection and preventive maintenance, which are reflected in the present study's findings on reduced scrap rates and energy consumption. However, the current implementation's OEE score of 85% and its specific reductions in scrap and energy consumption provide more concrete quantitative benefits compared to earlier qualitative assessments. Furthermore, the proposed future integration of AI and IoT for predictive maintenance and advanced analytics represents a forward-looking enhancement not extensively covered in previous studies, suggesting a trend towards even more sophisticated and data-driven automation solutions in industrial environments.

6 Conclusion

In conclusion, the PLC & HMI controlled extrusion machine monitoring system has demonstrated substantial improvements in operational efficiency, production quality, and waste reduction. By integrating the LS Industrial Systems XGB Series PLC and XGT Panel Series HMI, the system achieved precise control over the extrusion process, maintaining speed within ±5% of the target and ensuring consistent product quality. This achievement resulted in an Overall Equipment Effectiveness (OEE) of 85%, calculated from a 95% availability, 90% performance efficiency, and 92% first-pass yield, showcasing significant enhancements in machine utilization and production output. The user-friendly HMI interface enabled operators to monitor real-time data, make prompt

adjustments, and respond swiftly to alerts, reducing setup times and enhancing overall operational efficiency. This operational improvement led to a notable reduction in material wastage and scrap, with scrap rates decreasing by 15% compared to previous manual operations. Additionally, the system achieved a 10% reduction in energy consumption due to optimized motor control and precise temperature management, contributing to cost savings and environmental sustainability. Looking forward, future enhancements could explore the integration of AI for predictive maintenance and IoT-enabled sensors for advanced data analytics, further optimizing production processes and supporting sustainable manufacturing practices. These advancements aim to continuously improve efficiency, reduce costs, and enhance product quality in industrial operations.

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