Optimising IIoT Control Systems at Demcon: Integrating MQTT, Sparkplug B, and ISA-88 for Unified Automation

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Abstract: This paper addresses the challenges in optimizing PLC-based industrial control systems at Demcon to meet IIoT standards. Through a collaboration with the University of Groningen (NL), we redesigned the architecture using MQTT and Sparkplug B to enable scalable, real-time communication and introduced a Unified Namespace (UNS) for seamless data exchange. The results demonstrate improved flexibility, scalability, and latency reduction, validating the approach in an industrial environment and highlighting its broader potential for IIoT adoption.

1 INTRODUCTION

Industry 4.0 has revolutionized manufacturing by integrating IIoT and advanced analytics, enabling real-time data exchange and decision-making. However, Demcon's PLC-based control systems face challenges in scalability, communication, and real-time monitoring, limiting their ability to meet evolving industrial demands.

This paper presents a case study on redesigning Demcon's architecture, leveraging MQTT and Sparkplug B for scalable communication and introducing a Unified Namespace (UNS) to standardize data flow. The redesign aimed to address bottlenecks in real-time control and enhance operational efficiency, providing a model for broader IIoT applications.

The remainder of the paper is structured as follows: Section 2 reviews relevant literature, Section 3.2 and 4 outline the case study and the methodology, and Section 5 presents the findings. The paper concludes with a discussion of implications (Section 6) and future directions (Section 7).

2 RELATED WORKS

Industry 4.0 and IIoT have rapidly transformed various sectors, improving efficiency, flexibility, and communication (Mohammed Saleem et al., 2024). AI, machine learning and IoT technologies drive this digital revolution, but challenges such as data management, security and workforce skills remain significant (Z. Jan et al., 2022). Applications extend beyond manufacturing, impacting healthcare, agriculture and education (Bharti Rana and S. Rathore, 2022), and automotive and transportation industries also benefit from increased customisation and productivity (Dheeraj Nimawat and B. Gidwani, 2021).

From past research on IIoT, MQTT has often been favored due to its lightweight nature, making it ideal for resource-constrained environments (G. Reddy, 2017). Comparative studies have shown its efficiency in terms of network overhead and latency compared to CoAP and OPC UA (Iglesias-Urkia et al., 2017). It has also been demonstrated that integrating MQTT with Sparkplug B supports efficient data streaming, with reduced traffic overhead and lower latency (Koprov et al., 2022). However, the choice between MQTT and other alternatives, such as OPC UA, depends on specific application scenarios, with each offering distinct advantages in industrial communication (Wang et al., 2022).

IoT communication protocols such as CoAP, MQTT and OPC UA have been evaluated based on metrics like latency, scalability and energy efficiency. CoAP often outperforms other protocols in throughput, while MQTT excels in resource-constrained environments (Silva et al., 2021). However, the se-

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lection of protocol remains application-dependent, as OPC UA can perform better in certain industrial scenarios (Rocha et al., 2019).

Integrating Operational Technology (OT) with Information Technology (IT) systems in industrial environments poses significant challenges due to interoperability and security concerns (Watson et al., 2017). Protocols like MQTT Sparkplug B and OPC UA have enabled seamless communication and vertical integration, enhancing flexibility in distributed control systems (Koprov et al., 2022). Security challenges in low-power IIoT devices have been mitigated through the use of integration gateways and improved models (Mantravadi et al., 2020).

The ISA-88 standard enhances batch process flexibility and standardisation across industries, including pharmaceuticals and manufacturing (Jim Parshall and Larry C. Lamb, 1999; De Minicis et al., 2014). Integrating ISA-88 with Industry 4.0 concepts and IIoT protocols (e.g., MQTT) has improved data flow and real-time process management (Garcia et al., 2022), reducing programming efforts and improving process flexibility (Neugschwandtner et al., 2013).

The Unified Namespace (UNS) standardises data flow, improving real-time communication and enterprise scalability (Abouzied et al., 2024; Li et al., 2021). MQTT Sparkplug B aids in achieving UNS by connecting Operational Technology networks to cloud platforms (Koprov et al., 2022). Emerging architectures, including Time-Sensitive Networking (TSN) and hybrid wired-wireless systems, offer further advancements in real-time performance and flexibility (Simon Brooks and Ecehan Uludag, 2018).

Edge computing enhances real-time data processing and bandwidth optimisation in IIoT systems (Qiu et al., 2020). AI and machine learning further improve predictive maintenance and process optimization by enabling real-time analysis of sensor data (Walas and Redchuk, 2021). Integrating AI models with IIoT improves fault detection and decision-making, thus enhancing industrial efficiency (Gandhi, 2023; Kliestik et al., 2023).

3 KEY DEFINITIONS AND SITE DESCRIPTION

Section (3) defines the key terms and technologies relevant to the work performed at Demcon. Section 3.2 describes the industrial collaborator's site and the issues faced in the production site, while section 3.3 highlights the various aspects of intervention in the architectural redesign.

3.1 Definitions and Technologies Used

- *Industrial Internet of Things (IIoT):* Connects machines and sensors in industrial environments for enhanced efficiency, automation, and real-time data analysis.
- *MQTT:* A lightweight messaging protocol ideal for IIoT, enabling real-time communication between constrained devices (Stanford-Clark and Truong, 2013).
- *Sparkplug B:* An MQTT extension providing structured data exchange and lifecycle management for IIoT devices (Solutions, 2016).
- *Unified Namespace (UNS):* A centralized repository for real-time data and metadata
- *PLC:* Programmable Logic Controllers used in automation to control machinery, though less scalable in modern IIoT environments.
- *TwinCAT:* A real-time PLC programming platform used in industries like manufacturing and pharmaceuticals.
- *ISA-88 Standard:* Provides guidelines for batch control, standardizing processes for flexibility and scalability. It defines three models: *Process Model* (production steps), *Physical Model* (manufacturing environment layers), and *Procedural Model* (logical sequence of actions for batch control).

3.2 Description of the Site

The site selected for this research and implementation is Demcon Industrial Systems[1], based in Groningen. The company was chosen for this project due to its efforts to modernize the control system architecture and adopt emerging Industrial Internet of Things (IIoT) technologies, making it an ideal partner for testing innovative IIoT solutions.

Demcon operates a sophisticated manufacturing environment that relies on PLCs to control industrial processes and its operations are divided into multiple production units, each equipped with specialised machinery and sensors. These units are connected through BRIX (see Figure 1), an internal architecture based on the traditional industrial pyramid architecture ((Martinez et al., 2021)). While effective for legacy processes, this architecture poses challenges in data flow, flexibility and scalability, particularly as Demcon plans to transition to a smart factory model.

[1] https://demcon.com/

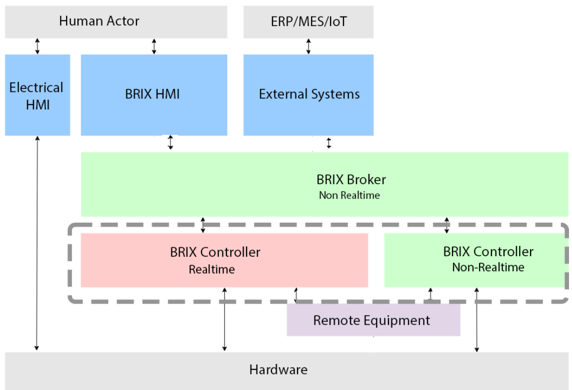

Figure 1: BRIX Architecture currently utilised in Demcon: the dashed line encloses the extent of the intervention described in this work.

The PLC also contains multiple automated modules that are abstracted according to the ISA-88 standard, as shown in Figure 2: redesigning them into a hybrid architecture was one of the aims of the work conducted within Demcon.

3.3 Formulation of the Problem

Demcon's control systems rely on rigid and inefficient PLCs programmed with TwinCAT, causing bottlenecks in data handling, real-time communication, and device integration. The hierarchical structure limits real-time data sharing across manufacturing levels, delaying decision-making and reducing efficiency. As operational demands grow, a unified communication protocol is needed to manage the increasing number of devices and sensors.

A key challenge is the lack of seamless integration between operational technology (OT) and information technology (IT) networks. Data collected at the PLC level is not efficiently communicated to SCADA, MES, and ERP systems, leading to delays in analytics and feedback, which impacts efficiency. Additionally, Demcon's reliance on TwinCAT limits system scalability and maintainability due to its rigid structure, not suited for the dynamic needs of IIoT systems.

Recognizing these limitations, Demcon aims to design a more flexible, agile system architecture using IIoT technologies like MQTT and Sparkplug B to enhance operational efficiency and scalability. Figure 1 illustrates Demcon's BRIX architecture, showing the interaction between control modules and OT.

The proposed intervention, shown in Figure 1 by a dashed grey rectangle, targets the controllers within the BRIX architecture. Currently, the ISA-88 based control modules (see Figure 2) are fully integrated into the real-time controller. This research proposes migrating most of these modules to a non-real-time controller, retaining only essential base modules in the real-time controller. Communication will occur through a unified namespace managed by a broker. The redesign of Demcon's controlling system architecture leverages IIoT technologies by focusing on the control logic within the PLC (the BRIX controllers in Figure 1), a key element of the traditional automation pyramid. The current system, limited by the PLC's memory and processing, operates in a rigid environment. A planned migration from a PLC-centred to a hybrid architecture moves the majority of system logic to a .NET environment, addressing these constraints and enabling more complex control logic and real-time data processing.

The intervention also implements the MQTT protocol with Sparkplug B as the backbone for communication between the migrated .NET modules and the PLC. MQTT's publish/subscribe model supports efficient data exchange across production, while Sparkplug B ensures unified data management and state control. This enhances scalability, enabling easier device integration and real-time production monitoring.

Finally, a unified namespace (UNS) standardises data flows between operational levels, serving as a "single source of truth" for system data. The UNS eliminates data exchange bottlenecks, consolidating communication into a coherent structure. This redesign improves flexibility and efficiency, allowing Demcon to adapt to evolving production demands.

4 METHODOLOGY

This section outlines the methodology used to redesign the industrial control system architecture at Demcon. The approach involved migrating upper-level control modules to a .NET environment while keeping lower-level control within PLCs. Communication between the two levels was facilitated by an MQTT broker, with the integration of Sparkplug B to extend MQTT functionality for real-time data exchange.

4.1 System Architecture Redesign

The system follows a hybrid architecture, where most ISA-88 abstraction layers were migrated from the real-time PLC system to .NET. Communication between the real-time and non-real-time components is facilitated by an MQTT broker (Figure 4). This shift addresses PLC memory and processing limitations, enabling more complex control logic and real-time data processing.

The modular architecture divides the system into

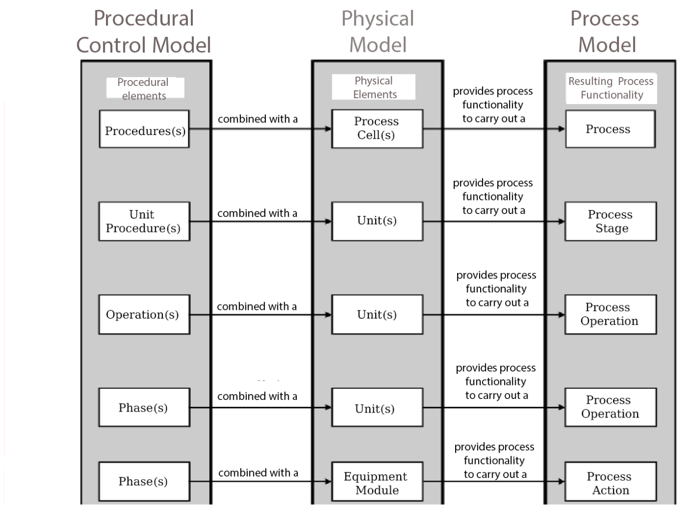

Figure 2: Diagram of the BRIX Controller built following the ISA88 standard.

independent components: **PLC modules** handle real-time control and lower-level tasks, while **.NET modules** manage upper-level logic and dynamic control flows. The **MQTT broker** acts as the central messaging hub, enabling publish/subscribe communication between modules. This modular approach enhances scalability, simplifies system updates, ensures fault isolation, and supports future expansions. Figure 3 illustrates these components and their interdependencies.

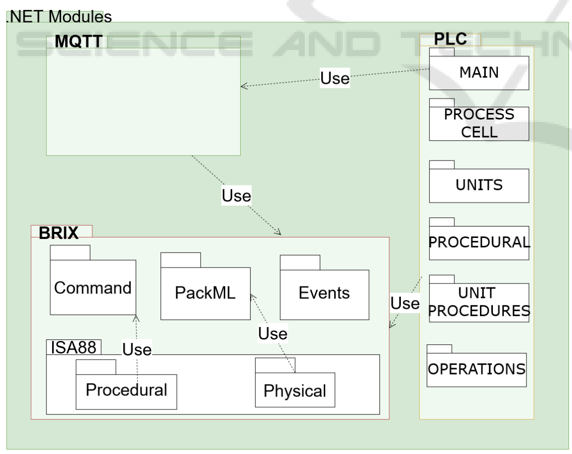

Figure 3: Modular view of .NET modules within the non-real-time controller (zoom-in representation from Fig 3).

A key part of the intervention was the implementation of a PLC-level broker (highlighted in yellow in Figure 4), which serves as a proof of concept for integration into the broader BRIX broker architecture. This will provide a more extensive unified namespace, enhancing flexibility and communication across the control system.

The system architecture shifted from a cycle-based PLC approach to an event-driven model in the .NET modules, where each subprocess triggers the next immediately. Physical elements change state or send notifications through the event system, enabling instant reactions to changes and maintaining continuous operation. This transition replaces fixed cycles with event-driven behavior, making the system more dynamic and closer to real-time operation.

4.2 Communication Protocol: MQTT and Sparkplug B

MQTT, augmented by Sparkplug B, was implemented to enable efficient real-time communication between the .NET modules, PLCs, and the MQTT broker. MQTT was chosen for its lightweight publish/subscribe model, ideal for low-bandwidth environments. Sparkplug B was used to standardize data formats, organize data into a hierarchical topic namespace, and support device lifecycle management through ”birth” and ”death” messages. These features helped improve system reliability. However, Sparkplug B was found to be incompatible with the existing system due to its rigid structure, limiting its utility in this specific case.

4.3 Data Monitoring and Collection

Real-time data monitoring was implemented using MQTT Explorer to validate the redesigned architecture. The tool visualized the data flow between the .NET modules, PLCs, and the MQTT broker, ensuring efficient communication through a Unified Namespace (UNS) based on system constraints and

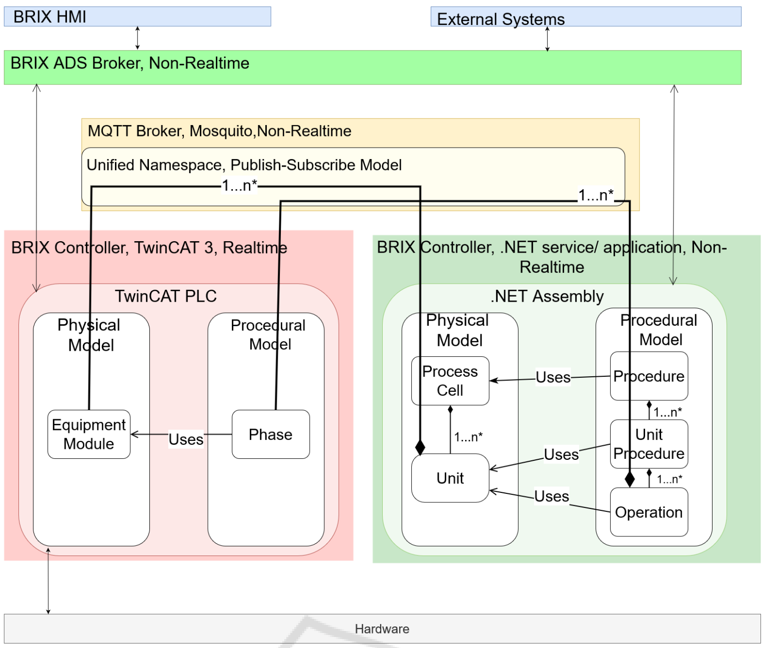

Figure 4: BRIX hybrid controller: Composition of ISA-88 abstraction modules, illustrating the division between real-time and non-real-time components. This zoomed-in view highlights the specific components and interactions within the BRIX controllers as shown in Figure 1.

inter-module relationships. The data streams included operational data from sensors, actuators, and PLCs, system status updates through lifecycle events, and control commands from .NET modules managing physical processes. Figure 5 shows the topic hierarchy used for monitoring, structured by module location and data scope.

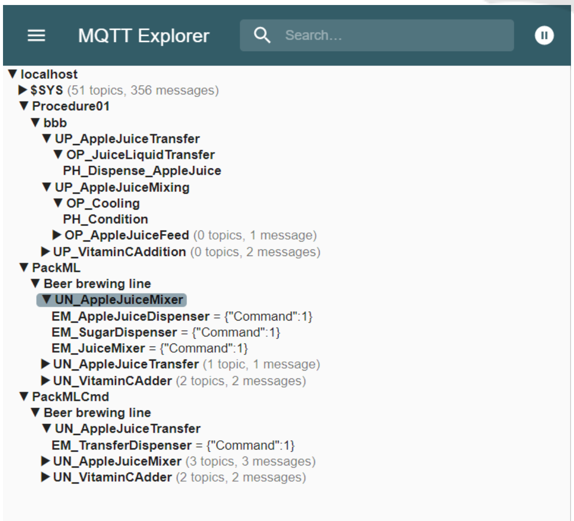

Figure 5: Screenshot taken from MQTT Explorer during system monitoring.

5 RESULTS AND EVALUATION

The project aimed to assess the feasibility of using MQTT and Sparkplug B for IIoT communication while designing a scalable control system. These objectives were successfully met, with MQTT enabling efficient communication. However, Sparkplug B exhibited limitations due to its rigid structure. The following analysis evaluates system functionality, performance, communication efficiency, and the integration feasibility of MQTT and Sparkplug B.

5.1 System Functionality and Performance

Transitioning from a PLC-based to a hybrid architecture combining PLCs and .NET modules enhanced system flexibility and scalability while retaining essential real-time control for industrial automation. This aligns with the broader trend of integrating legacy systems with modern architectures to meet Industry 4.0 and IIoT requirements (Sheetal M. Solanki, 2023; Mohammed Saleem et al., 2024).

The modular design of the .NET-based architecture greatly improved flexibility, allowing for independent development of control modules. This facilitated easier updates and maintenance while enabling seamless future expansions without disrupting the system's existing functionality. In IIoT contexts, such modularity is critical for scaling and reconfiguring systems to meet evolving industrial demands (Garcia et al., 2022). Additionally, the event-driven model in .NET provided dynamic control, making the system more responsive compared to the cyclic execution inherent in traditional PLCs. This adaptability is a cornerstone of Industry 4.0, where operational efficiency depends on swift responses to changing conditions (Walas and Redchuk, 2021).

Scalability was also a significant improvement, supported by MQTT's publish/subscribe model. This architecture efficiently managed multiple devices and data streams, minimising communication overhead. The lightweight nature of MQTT messaging ensured that modules only subscribed to relevant topics, reducing unnecessary data exchange and optimising communication efficiency. This characteristic makes MQTT particularly suitable for resource-constrained environments (G. Reddy, 2017).

5.2 Communication Efficiency

The integration of MQTT resulted in noticeable improvements in communication efficiency. By utilising its publish/subscribe model, the system facilitated immediate data transmission between publishers, such as PLCs and sensors, and subscribers, such as .NET modules. This mechanism ensured consistently low latency, with most messages being delivered within 100 milliseconds. Such performance is essential for industrial applications requiring real-time control and aligns with findings in other studies that highlight MQTT's advantages over alternative protocols such as CoAP and OPC UA (Rocha et al., 2019).

5.3 Feasibility of MQTT and Sparkplug B in IIoT Systems

The study examined the feasibility of integrating MQTT and Sparkplug B within an IIoT framework: MQTT demonstrated high effectiveness in supporting real-time communication, ensuring tight interaction between various system components. Sparkplug B proved less suitable due to its rigid payload structure and strict device-oriented namespace rules. These limitations introduced redundancy and complexity, rather than enhancing scalability or data management. While the system benefited from MQTT's low-latency data exchange, which supported real-time monitoring and control, Sparkplug B's inflexible format hindered its broader applicability (De Minicis et al., 2014; Neugschwandtner et al., 2013).

5.4 Limitations and Challenges

Despite the successes, the system faced several limitations. One significant challenge was the compatibility of Sparkplug B, whose rigid structure and strict namespace rules were poorly suited to the PLC architecture. This led to increased redundancy and complexity without providing notable improvements in data management. Another limitation was the lack of real-world testing. The system relied on static recipes and simulated data, restricting its exposure to dynamic, real-world industrial conditions. To fully evaluate long-term performance, testing in practical environments is necessary (Walas and Redchuk, 2021).

Furthermore, this study focused on developing a proof-of-concept rather than a fully implemented solution, meaning there are no direct performance comparisons to traditional PLC systems at this stage. The results presented here demonstrate the feasibility of the proposed hybrid architecture and communication protocols, serving as a foundation for future research. The integration of MQTT showed clear benefits in communication efficiency, while the challenges identified with Sparkplug B suggest areas for further development. Future work will focus on completing the migration of control modules to .NET, optimizing system performance, and conducting real-world testing to validate the system's scalability and robustness in industrial environments.

6 DISCUSSION AND LESSONS LEARNT

The results of the system redesign highlight the feasibility of integrating MQTT and Sparkplug B into industrial control architectures. This section explores the broader implications of the findings, lessons from the system redesign, and the potential for applying the architecture to other industrial contexts.

6.1 Key Takeaways

The transition from a traditional PLC-centric system to a hybrid architecture provided insights into the challenges and opportunities of IIoT-based industrial automation. Combining PLCs with .NET-based control modules proved advantageous, retaining the reliability of PLCs for real-time control while leveraging the flexibility of .NET for higher-level logic. This hybrid approach enabled a more adaptive system without compromising reliability, aligning with industry trends towards scalable and adaptable control systems (Walas and Redchuk, 2021).

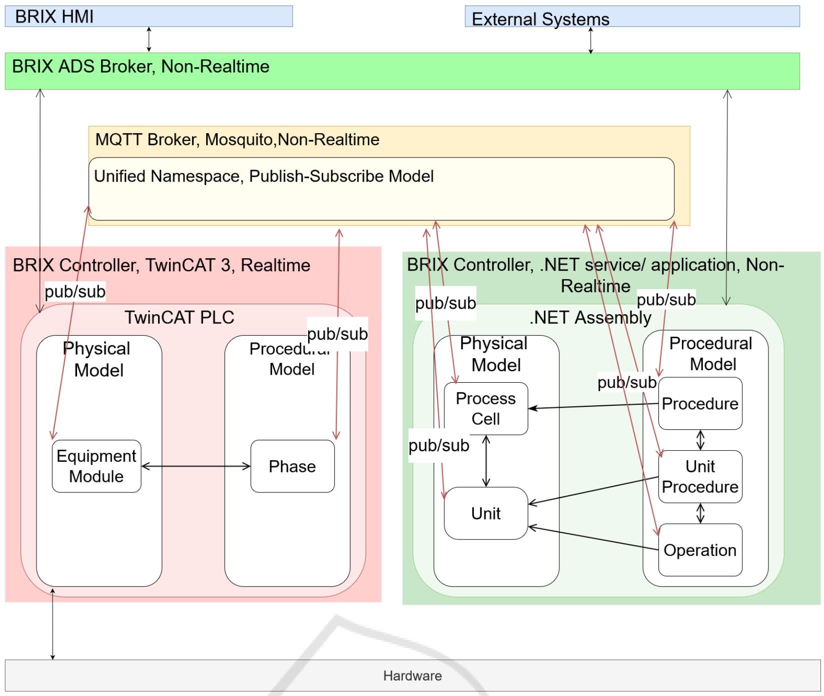

Figure 6: Enhanced communication in BRIX controllers enabled by MQTT and a unified namespace. Red lines represent new communication channels; black lines depict improved existing connections, derived from legacy architecture.

Standardised communication protocols also played a vital role, as evidenced by the effectiveness of MQTT. The adoption of MQTT facilitated seamless, scalable communication across diverse devices and platforms. Literature supports this observation, noting that protocols like MQTT and Sparkplug B simplify the management of complex systems while reducing development and maintenance efforts (Iglesias-Urkia et al., 2017).

6.2 Applicability to Other Industries and Future Extensions

This study's findings are applicable beyond Demcon's systems, offering a versatile model for industries adopting IIoT technologies, including energy, healthcare, and logistics. The architectural design, particularly the use of MQTT and Sparkplug B, aligns well with requirements in smart factories and distributed energy systems, where real-time data exchange is crucial (Koprov et al., 2022). Additionally, the architecture provides a foundation for integrating advanced technologies, such as AI for predictive maintenance and edge computing for enhanced real-time processing. As IIoT evolves, these features position the architecture to address emerging trends in Industry 4.0 (Waghanna et al., 2024).

7 CONCLUSION

This study presents the successful redesign of a PLC-based control system into a flexible scalable hybrid architecture using MQTT and Sparkplug B. The system combines PLCs' real-time control with the dynamic, event-driven nature of .NET modules, improving scalability, communication efficiency, and modularity. MQTT enabled efficient communication, while Sparkplug B standardized data, allowing seamless integration across system components and supporting the evolving demands of industrial automation.

While the architecture was effective in controlled testing, challenges with Sparkplug B compatibility and limited real-world testing show areas for further investigation. The architecture has broader potential for industries like manufacturing, energy, healthcare, and logistics, which could benefit from the flexibility and efficiency of IIoT-based control systems.

In conclusion, this research laid the groundwork for further development of hybrid architectures at Demcon, offering a path for integrating modern communication protocols and real-time data processing into traditional manufacturing environments.

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