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A Standardized and Interoperable Approach for Multi-Vendor DAS–DIS Integration in Continuous Emission Monitoring Systems

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Abstract: The increasing complexity of industrial emissions and the limitations of conventional monitoring systems have created an urgent need for reliable, real-time, and interoperable emission monitoring solutions. In Continuous Emission Monitoring Systems (CEMS), the integration of heterogeneous data from multi-vendor Data Acquisition Systems (DAS) remains a major challenge, particularly in relation to data consistency, interoperability, and regulatory compliance. **Objective:** This study aims to develop an integrated DAS–DIS framework that standardizes data processing and communication across heterogeneous industrial environments. **Method:** This research employed a system engineering approach using a prototype-based development method. Data sources included regulatory documents, technical standards, and simulated emission datasets in CSV, XML, and JSON formats. The system was designed using a JSON-based Unified Data Model (UDM), supported by ISO 8601 timestamps, quality codes, HMAC-based digital signatures, and hybrid HTTP–MQTT communication protocols. Functional testing and simulation were conducted to evaluate data transformation, validation, and transmission. **Findings:** The results show that the proposed system can transform heterogeneous DAS outputs into a consistent and standardized structure while maintaining data integrity and reliability. JSON schema validation and digital signatures support secure data exchange, while the hybrid communication architecture enables both regulatory reporting and real-time monitoring. **Implications:** The proposed framework can improve interoperability, reliability, and operational efficiency in industrial emission monitoring systems, while also supporting regulatory compliance and data-driven environmental management. **Originality:** This study offers an integrated and application-oriented framework that combines data standardization, communication architecture, and validation mechanisms within a single system specifically designed for multi-vendor CEMS integration.

Keywords: CEMS; DAS–DIS integration; Unified Data Model; interoperability; HTTP–MQTT hybrid.

INTRODUCTION

The rapid growth of industrial activities and urbanization has led to a significant decline in air quality in many developing countries, including Indonesia. Industrial emissions from sectors such as power generation, manufacturing, and resource processing are among the major contributors to air pollution, directly affecting human health and the environment. Exposure to pollutants such as SO_2, NOx, CO, and particulate matter has been associated with an increased risk of respiratory and cardiovascular diseases, as well as a decline in overall quality of life (Wang et al., 2025; World Health, 2021). In this context, continuous emission monitoring has become a critical component of modern environmental management systems. The Continuous Emission Monitoring System (CEMS) plays an essential role in providing real-time emission data, enabling industries and regulators to assess environmental impacts and implement data-driven mitigation strategies (United States Environmental Protection, 2023; Zolotova et al., 2025).

In Indonesia, the need for reliable emission monitoring systems has become increasingly urgent due to the growing complexity of pollution sources and the limitations of conventional monitoring approaches. Studies indicate that centralized and non-real-time air quality monitoring systems often fail to provide timely and accurate data for effective environmental decision-making, resulting in delayed responses to pollution events and weakened emission control practices (Herawan, 2026; Nugroho et al., 2025). Furthermore, recent research highlights that sensor-based and IoT-enabled monitoring systems can significantly improve data accuracy, continuity, and responsiveness compared to traditional approaches (Kumar et al., 2022). Therefore, the development of real-time, integrated, and interoperable emission monitoring systems is crucial for improving air quality management in Indonesia.

From the literature perspective, previous studies can be categorized into three main groups. The first category focuses on CEMS and industrial emission monitoring systems, primarily addressing measurement accuracy, system reliability, and regulatory compliance. (Choi et al., 2022) demonstrated that pretreatment systems can improve CEMS measurement performance by reducing interference from moisture and particulates. In addition, international standards such as USEPA 40 CFR Part 60 and EN 14181 emphasize the importance of Quality Assurance/Quality Control (QA/QC) procedures to ensure data reliability. Other studies also indicate that digital integration within CEMS enhances reporting efficiency and supports real-time environmental monitoring (Choi et al., 2022; United States Environmental Protection, 2023; Wang et al., 2025). However, most research in this category remains focused on instrumentation and data validation, with limited attention to multi-vendor system integration challenges.

The second category addresses interoperability in Internet of Things (IoT) and Industrial IoT (IIoT) systems, highlighting the complexity of integrating heterogeneous systems. A systematic study by Bures identified interoperability as a key challenge due to differences in communication protocols, architectures, and data representations (Bureš et al., 2020). Kovács further emphasized the importance of semantic interoperability to ensure that exchanged data can be meaningfully interpreted across systems (Kovacs et al., 2016). In terms of communication technologies, several studies have compared protocols such as MQTT, CoAP, and HTTP, demonstrating differences in latency, efficiency, and reliability (Bayılmış et al., 2022; Gündoğan et al., 2018; Thangavel et al., 2014; Tran et al., 2024). Additional research suggests that no single protocol is universally optimal, and adaptive or hybrid approaches are often required (Al-Fuqaha et al., 2015). Despite these advances, most studies remain generic and are not specifically tailored to industrial emission monitoring systems such as CEMS, which require stricter data validation and regulatory compliance.

The third category focuses on standardized data models and semantic interoperability for sensor data exchange. Approaches such as oneM2M and NGSI-LD have been developed to provide consistent and interoperable data models across heterogeneous IoT platforms (Kumar et al., 2022). Other studies demonstrate that JSON-based data models and semantic interoperability frameworks can improve cross-platform data integration (Datta et al., 2014; Mineraud et al., 2016). Furthermore, research highlights that complex systems often require hybrid communication architectures to achieve scalability and efficiency (Kashyap & Sharma, 2025). However, most of these approaches remain conceptual or simulation-based and have not been extensively implemented in industrial environments such as CEMS, where multiple real-world data formats (e.g., CSV, XML, JSON) must be handled simultaneously.

Based on these three research streams, it is evident that CEMS research has been well developed in terms of measurement and validation, IoT research has advanced interoperability concepts, and data model research has provided standardization frameworks. Nevertheless, a significant research gap remains, as few studies have integrated these three aspects simultaneously within a practical and implementable framework, particularly for multi-vendor DAS–DIS integration in CEMS environments. This gap highlights the need for a solution that combines standardized data models, flexible communication protocols, and practical implementation strategies tailored to industrial and regulatory requirements.

To address this gap, this study aims to develop an interoperable and standardized multi-vendor DAS–DIS integration system for CEMS using a Unified Data Model (UDM) based on JSON and a hybrid communication architecture combining HTTP and MQTT protocols. Specifically, this research focuses on designing a unified data structure capable of accommodating heterogeneous data formats, developing data validation mechanisms including ISO 8601 timestamps, quality codes, and HMAC-based digital signatures, and implementing a prototype system capable of supporting real-time monitoring and regulatory reporting in industrial environments.

This study proposes the argument that the integration of a standardized data model, hybrid communication protocols, and robust data validation mechanisms can significantly enhance interoperability, data consistency, and system reliability in multi-vendor DAS–DIS environments. Standardizing the data model is expected to reduce data transformation complexity and minimize interpretation errors, while the use of hybrid communication protocols enables separation between regulatory reporting (HTTP) and real-time internal data distribution (MQTT), improving system flexibility and efficiency. Furthermore, the incorporation of validation mechanisms such as quality codes, standardized timestamps, and digital signatures is anticipated to strengthen data integrity and trustworthiness. Therefore, the main hypothesis of this study is that the integration of these three components will result in a more robust, interoperable, and scalable CEMS system compared to conventional non-standardized approaches.

RESEARCH METHOD

This study focuses on the development and implementation of a multi-vendor integration system for Data Acquisition System (DAS) and Data Interface System (DIS) within the context of Continuous Emission Monitoring Systems (CEMS). The primary unit of analysis in this research is the data integration process of emission monitoring systems, including the transformation, validation, and transmission of emission data generated by various DAS devices. In particular, the study examines how heterogeneous data formats (e.g., CSV, XML, JSON) from multiple vendors can be standardized into a unified structure and reliably transmitted to regulatory and internal monitoring systems. Therefore, the analysis emphasizes system architecture, data interoperability, and communication mechanisms as the core objects of investigation.

This research adopts a system engineering approach using a prototype-based development method. This approach is selected because the study aims not only to analyze an existing phenomenon but also to design and implement a functional system that can address real-world integration challenges. The prototype method allows iterative development, testing, and refinement of the system, ensuring that the proposed solution is both technically feasible and practically applicable. This design is particularly suitable for addressing complex engineering problems involving multi-vendor systems, where flexibility and adaptability are essential for achieving interoperability and system reliability.

The data used in this study consist of both secondary and system-generated data. Secondary data include regulatory documents related to CEMS implementation, international standards, and technical references on data communication and interoperability. In addition, system-generated data are obtained from simulated and real emission monitoring scenarios, including datasets representing various vendor-specific formats such as CSV, XML, and JSON. These datasets contain parameters such as SO_2, NOx, CO, timestamps, and quality indicators, which are used to evaluate the capability of the proposed system in handling heterogeneous data sources.

Data collection in this research is conducted through a combination of literature review, system simulation, and experimental implementation. The literature review is used to identify regulatory requirements, technical standards, and existing approaches related to CEMS and IoT interoperability. System simulation is performed by generating emission data scenarios that represent different vendor configurations, enabling controlled testing of data parsing, transformation, and validation processes. Furthermore, experimental implementation is carried out by developing a prototype system using Python and Node.js, integrating HTTP and MQTT communication protocols, and utilizing tools such as Postman, MQTT.fx, and Wireshark to test system functionality, data transmission, and network performance.

The data analysis process is conducted through a functional and performance-based evaluation of the developed system. The analysis includes several stages: (1) data parsing and transformation from multiple input formats into a unified JSON-based structure; (2) validation of data integrity using JSON schema, quality codes, and HMAC-based digital signatures; (3) evaluation of communication performance through HTTP and MQTT protocols; and (4) assessment of system interoperability across different simulated and real-world scenarios. The results are analyzed descriptively to determine the effectiveness of the proposed architecture in achieving data consistency, interoperability, and reliable transmission within a multi-vendor CEMS environment.

RESULTS

Implementation of the DAS–DIS Integration System

At the current stage, the technical implementation of the DAS–DIS integration system has been completed and has been deployed in several industrial client environments as part of the initial validation phase. The implemented system focuses on three main components, namely data conversion, the development of a universal JSON-based format through a Unified Data Model (UDM)**,** and the design of a communication flow capable of supporting data exchange across multi-vendor devices. Although full-scale field testing has not yet been formally documented, the developed prototype demonstrates that the proposed architecture is technically operable and ready for structured evaluation.

The implemented system enables heterogeneous emission data generated by different DAS devices to be normalized into a unified structure before being transmitted to external and internal endpoints. The data model includes key fields such as device_id, timestamp, parameters, quality_code, and signature, allowing the system to standardize the representation of emission information originating from different vendor-specific formats. In addition, the communication architecture has been prepared to support both HTTP-based transmission for external reporting and MQTT-based streaming for internal real-time monitoring.

Figure 1. General workflow of the implemented DAS–DIS integration system.

Initial Functional Readiness for System Testing

The initial system readiness has been organized around four core testing aspects, namely input format handling, data structure validation, digital signature simulation, and communication delivery. These aspects were selected because they represent the main technical requirements for achieving interoperability in a multi-vendor CEMS environment. Rather than reporting final quantitative performance metrics, the present stage confirms that the corresponding modules and procedures for each aspect have been successfully prepared and integrated into the prototype environment.

The first aspect concerns the ability of the system to extract and transform emission data from multiple input formats. The second aspect addresses the compliance of transformed data with the predefined JSON schema. The third aspect covers the simulation of HMAC-SHA256-based digital signatures to support payload integrity verification. The fourth aspect concerns the readiness of the communication mechanism for sending data to HTTP endpoints and MQTT brokers. These four aspects form the basis for subsequent formal evaluation under broader field conditions.

Table 1. Implemented testing aspects and associated technical methods

Testing Aspect	Method	Tool/Library
CSV parsing	DictReader	Python
XML parsing	ElementTree	Python / VS Code
JSON parsing	Native JSON validation	Postman
Schema validation	JSON Schema Draft-07	Python Validator
Signature simulation	HMAC-SHA256	hashlib (Python)
HTTP transmission	HTTP POST (REST API)	Postman / Insomnia
MQTT transmission	QoS 1 topic publish	MQTT.fx / Mosquitto

Unified Data Model Output Structure

One of the main outputs of this study is the design and implementation of a unified JSON structure that can accommodate heterogeneous DAS outputs in a consistent format. The developed Unified Data Model was designed to represent the essential elements required for emission data exchange, including device identity, timestamp standardization, emission parameters, quality code, and payload authentication. This structure serves as the intermediate layer between raw DAS output and the communication layer used for delivery to regulatory and internal systems.

The use of a unified structure allows data originating from CSV, XML, or JSON sources to be transformed into a single machine-readable format. This output design is intended to reduce integration complexity and provide a consistent payload structure for downstream processing. At the current stage, the data model has been implemented at the prototype level and is ready to be used as the basis for further testing and field documentation.

Table 2. Main fields in the implemented Unified Data Model

Field	Description
device_id	Unique identifier of the DAS/analyzer source
timestamp	Standardized time format using ISO 8601

Field	Description
parameters	Emission parameters such as SO_2, NOx, CO, and O_2
quality_code	Data validity indicator (e.g., OK, ERR, CAL)
signature	HMAC-based digital signature for payload integrity

An example of the implemented output structure is shown below.

```
{
  "device_id": "DAS-001",
  "timestamp": "2025-12-13T15:30:00Z",
  "parameters": {
    "SO2": { "value": 35.2, "unit": "mg/Nm3" },
    "NOx": { "value": 18.6, "unit": "mg/Nm3" }
  },
  "quality_code": "OK",
  "signature": "a94f3e..."
}
```

Dashboard and Monitoring Interface Readiness

The implemented DAS–DIS system has also been connected to a web-based monitoring dashboard designed for both internal and external observation purposes. The dashboard has been deployed in several industrial client environments and is intended to visualize emission data and connection status in near real-time through MQTT-based architecture. At the current stage, the dashboard serves as an operational interface that reflects the readiness of the communication and visualization layers of the system.

The dashboard includes several key monitoring features, namely an interactive map of emission source locations, periodic device connection status updates, numerical and graphical displays of selected emission parameters, and color indicators based on quality_code. In addition, a 24-hour historical view and anomaly notification mechanisms through webhook or Telegram integration have been prepared as part of the monitoring environment. Although screenshots and field evidence are reserved for the final documented version, the functional design of the dashboard indicates that the visualization layer has been successfully aligned with the system architecture.

Table 3. Functional elements of the monitoring dashboard

Dashboard Feature	Description
Interactive map	Displays industrial emission source locations using GPS coordinates
Device status	Indicates online, offline, or inactive DAS status
Real-time graph	Displays SO_2, NOx, O_2, and CO values in graphical form
Numeric snapshot	Shows current numerical values of monitored parameters

Dashboard Feature	Description
Quality indicator	Color-based display using quality_code
Historical records	Displays the last 24 hours of data
Notifications	Sends anomaly alerts via webhook or Telegram

System Flow Representation and Technical Readiness

The developed system flow represents the end-to-end integration process from analyzer-level data generation to external and internal distribution. Emission data are first acquired by analyzers and collected by DAS devices in different output formats. These outputs are then processed by the DIS layer, where parsing, normalization, schema validation, and digital signature generation are performed. After validation, the resulting payload is routed either to an HTTP endpoint for reporting purposes or to an MQTT broker for internal streaming and dashboard visualization.

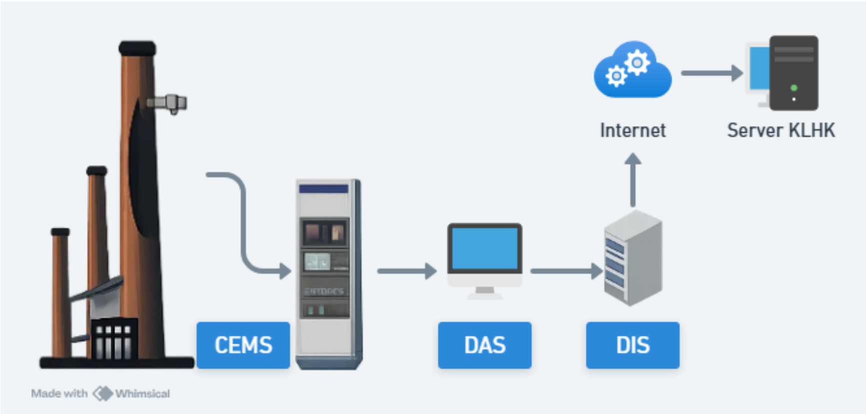

Figure 2. System Integration Diagram of DAS and DIS

At this stage, the main result of the study is not a finalized performance benchmark, but rather a technically validated architecture that has demonstrated readiness for structured evaluation. Internal implementation and semi-operational use indicate that the proposed system can support heterogeneous DAS data structures and communication requirements. Furthermore, the preparation of system logs for transmission time, server responses, payload anomalies, and signature verification provides a basis for the next stage of formal performance analysis.

DISCUSSION

The results of this study indicate that the proposed DAS–DIS integration system has reached a stage of technical readiness and functional operability, particularly in handling heterogeneous data formats, applying a unified data structure, and supporting dual communication protocols. The system demonstrates the capability to normalize multi-vendor DAS outputs into a consistent JSON-based structure while ensuring data validation through schema enforcement and digital signature mechanisms. In addition, the integration of HTTP and MQTT communication protocols has enabled the system to support both regulatory reporting and real-time monitoring within a single architecture. These findings confirm that the designed framework is capable of addressing key interoperability challenges in CEMS environments.

The observed results can be explained by the adoption of a Unified Data Model (UDM) and a modular system architecture. The use of a standardized JSON structure reduces the complexity of transforming heterogeneous input data, thereby minimizing inconsistencies during data exchange. Furthermore, the implementation of validation mechanisms such as JSON schema, quality codes, and HMAC-based signatures ensures that data integrity and reliability are maintained throughout the transmission process. The separation of communication pathways HTTP for external reporting and MQTT for internal streaming also contributes to system efficiency by allowing each protocol to operate according to its strengths. These design choices explain why the system is able to function consistently across different data sources and communication requirements.

When compared with previous studies, the findings of this research align with existing literature that emphasizes the importance of standardization and interoperability in IoT-based systems. Prior studies have demonstrated that heterogeneous systems require unified data representation and adaptive communication strategies to achieve effective integration. However, most of these studies remain either focused on instrumentation (in the case of CEMS) or on general interoperability frameworks (in the case of IoT research). In contrast, this study contributes a more integrated and application-oriented approach by combining data standardization, hybrid communication protocols, and validation mechanisms within a single system specifically designed for CEMS multi-vendor environments. This integration represents a key novelty, as it bridges the gap between conceptual interoperability models and practical industrial implementation.

From an interpretative perspective, the results suggest that the integration of standardized data models and hybrid communication architectures can significantly enhance the reliability and flexibility of environmental monitoring systems. This implies that future industrial monitoring systems should move toward data-centric architectures, where interoperability is achieved through shared data standards rather than rigid system dependencies. The findings also highlight the importance of incorporating security mechanisms, such as digital signatures, as a fundamental component of data exchange in industrial and regulatory contexts. Consequently, this study contributes to a broader understanding of how modern monitoring systems can evolve toward more scalable and trustworthy architectures.

Nevertheless, several limitations must be acknowledged. The current results are primarily based on prototype implementation and controlled simulation scenarios, with limited formal documentation of large-scale field testing. As a result, quantitative performance metrics such as latency, throughput, and system scalability under real industrial loads have not yet been fully evaluated. Additionally, while the proposed architecture demonstrates flexibility, its implementation may require adaptation depending on specific industrial infrastructures and regulatory requirements. These limitations highlight the need for further validation to fully assess the robustness and generalizability of the proposed system.

Based on these findings, several practical implications and future actions can be proposed. First, regulatory bodies and industrial stakeholders should consider adopting standardized data models to improve interoperability across monitoring systems. Second, the use of hybrid communication architectures should be encouraged to support both real-time monitoring and formal reporting requirements. Third, future research should focus on conducting large-scale field testing and performance benchmarking to validate the system under real operational conditions. Finally, the integration of advanced analytics, such as anomaly detection and predictive modeling, can be explored to enhance the functionality of the system beyond data integration. These actions are expected to contribute to the development of more reliable, scalable, and intelligent emission monitoring systems in industrial environments.

CONCLUSION

This study demonstrates that the proposed DAS–DIS integration system is capable of addressing key challenges in multi-vendor emission monitoring environments through a standardized and interoperable approach. The main finding shows that the implementation of a Unified Data Model (UDM) combined with hybrid communication protocols (HTTP and MQTT) enables the system to transform heterogeneous DAS outputs into a consistent and structured format. In addition, the integration of validation mechanisms, including JSON schema, quality codes, and HMAC-based digital signatures, ensures data integrity and reliability throughout the data transmission process. These results indicate that the system is technically feasible and functionally ready to support real-time monitoring and regulatory reporting within CEMS frameworks.

From a scientific perspective, this research contributes to the field of industrial IoT and environmental monitoring by proposing an integrated and application-oriented framework that combines data standardization, communication architecture, and validation mechanisms within a single system. Unlike previous studies that tend to focus on isolated aspects such as instrumentation, interoperability theory, or communication protocols, this study provides a more comprehensive approach tailored to real-world industrial requirements. The introduction of a JSON-based Unified Data Model for DAS–DIS integration, along with a hybrid HTTP–MQTT communication scheme, represents a practical contribution that can be adopted or further developed in similar multi-vendor monitoring systems.

However, this study has several limitations that should be acknowledged. The results are primarily based on prototype implementation and initial deployment scenarios, with limited formal documentation of large-scale field testing and quantitative performance evaluation. Metrics such as latency, throughput, and system scalability under real operational conditions have not yet been comprehensively analyzed. Therefore, future research is recommended to conduct extensive field validation, performance benchmarking, and long-term system monitoring. Additionally, further development could explore the integration of advanced analytics, such as anomaly detection and predictive modeling, to enhance the system's functionality and support more intelligent decision-making processes in industrial emission management.

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