IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 8 December 2025, accepted 4 January 2026, date of publication 14 January 2026, date of current version 20 January 2026.
Digital Object Identifier 10.1109/ACCESS.2026.3654252

RESEARCH ARTICLE

Industry 5.0: An Extended Experimental Case for Implementing a Multi-Level Framework for Enterprise Integration

IOANA-VICTORIA NITULESCU, ADRIAN KORODI, (Member, IEEE), AND DANIEL-IOAN CURIAC, (Senior Member, IEEE)
Department of Automation and Applied Informatics, Faculty of Automation and Computers, Polytechnic University of Timisoara, 300006 Timisoara, Romania
Corresponding author: Adrian Korodi (adrian.korodi@upt.ro)

This work was supported by the Project "Innovative Technological Approaches to Circularity and Urban-Industrial Symbiosis within the Water-Energy-Materials-Fertilizers Nexus (ECO-NEXUS)", Smart Growth, Digitalization and Financial Instruments Program, 2021-2027, MySMIS under Grant 336912.

ABSTRACT With the rapid momentum of the Industry 5.0 paradigm due to its projected socio-economic impact, it has become essential to interpret its requirements into a concrete form. This study concentrates on an extended experimental use case, constructing a multi-level approach to address the identified challenges concerning system integration, digital transformation, interoperability, and OT-IT convergence at enterprise level. The experiment aims to evaluate a functional framework for the adoption of Industry 5.0, enhancing cooperation and collaboration, improving stability for future development and integration objectives, while respecting the general architectural design of the organizational infrastructure. The prototype involved the successful formation of a highly available enterprise infrastructure, introducing a modular development structure for Node-RED flows, augmenting system compatibility, transfer mechanisms, and protocols, including a fully dynamic data acquisition and standardization phase. The refined solution facilitates informed decision-making processes for involved personnel, while merging the OT and IT domains within an open-source, scalable, dynamic, highly-customizable and flexible framework, with minimal implementation and operational costs. This scholarly work underscores the importance of advancing towards contemporary data architectures that support and sustain growing data volumes, enhance user experience, and usability in operational processes. It champions an ideology that places scalability at the core of enterprise architecture strategies, thereby promoting advancements, performance, and growth opportunities through a single-source-of-truth (SSOT).

INDEX TERMS Data, Industry 5.0, integration, interoperability, node-RED, OT-IT convergence, standardization, virtualization.

I. INTRODUCTION

Industry 5.0 (I5.0) defines a transitory state in the direction of a mentality shift constructed on three main pillars: human-centricity, sustainability and resilience [1]. Its main objective is to emphasize collaboration and innovation for a positive societal impact, accentuating human participation [2], [3] in technological and operational processes, while simultaneously underlining the importance of sustainable development [4] and green practices [5] for the environment.

The associate editor coordinating the review of this manuscript and approving it for publication was Claudio Zunino.

It can be considered a complementary effort emerging from the Industry 4.0 (I4.0) paradigm, which focuses on automation and Digital Transformation (DT) [6]. The main key technologies of Digital Transformation include: Internet of Things (IoT), Cloud Computing, Artificial Intelligence (AI), Digital Twins, Robotic Automation Processes (RPA) and other strategic development tools.

The implications of an interconnected and digitalized world are not limited to local applications in the context of an Industrial Internet of Things (IIot) mesh, but introduce the concept of operation technology (OT) and information technology (IT) convergence [7]. OT implies designated software and hardware, which interact with physical devices, processes and industrial infrastructure elements (Supervisory Control and Data Acquisition - SCADA, Geographic Information System - GIS, Distributed Control Systems - DCS, Programmable Logic Controllers - PLC etc.) from multiple sectors. IT comprises enterprise solutions that manage heterogeneous data, varied applications and digital infrastructure. In spite of these two layers being distinct and uncorrelated, they pertain to crucial roles within contemporary organizations [8]. Thus, coexistence and convergence of the OT and IT levels is complex and marked by numerous hindrances, as they belong to different worlds and scopes [9].

The persistent utilization of legacy systems within organizations serves as a fundamental obstacle to digital transformation efforts, mainly due to their outdated protocols and inefficiencies, despite their essential role in supporting critical processes [10]. Legacy systems are antiquated technologies that remain essential to organizations due to their support of key business operations, yet they struggle with inefficiencies and lack the connectivity features present in modern solutions [11]. This reliance on legacy systems contributes to organizational complexity and poses challenges, especially as companies attempt to adopt newer digital tools and solutions.

Inflexibility, compatibility issues, lack of functionalities, challenges in data transfers, disruption of ongoing business-critical processes and ingrained resistance to change confine inherent liabilities correlated with legacy system integration [12]. The seamless integration of these systems with modern technologies involves adoption of new and effective methodologies in terms of planning and development, ultimately leading to harnessing innovation while utilizing the current existing infrastructure.

This becomes paramount in the interconnected modern world, especially considering the transition to the Industry 5.0 paradigm and its corelation with Society 5.0 [13], but methodologies and solutions are not clearly defined for this specific kind of accelerated adaptation; therefore, in-depth studies of OT-IT convergence becomes a key component for modern enterprise architectural designs and industrial practices.

The scope of this manuscript, which builds upon our conference paper [14], is to propose an incipient architecture for standardized OT-IT convergence, supporting organizations on their journey to digitalization goals, while maintaining ongoing business processes, with Industry 5.0 pillars in mind.

The paper is assembled as follows: section II will contour the current industrial context in an ample manner, by reviewing the available specialized literature, highlighting limitations, challenges and research gaps. Section III will cover the Solution Development practices utilized in this manuscript, alongside valuable implications on the viable architectural designs for achieving coexistence and interconnection. Chapter IV will analyze and discuss the results and achievements of this paper. Lastly, the final part of the paper will cover the drawn conclusions, their impact for the completed study and future directions for researching the opportunities introduced by this study.

II. LITERATURE REVIEW

As previously mentioned, Industry 5.0 delineates a complementary approach to Industry 4.0, thus creating a co-existence mentality between the two concepts [15]. Among these lines, in paper [16], a more in-depth analysis is conducted to understand the real implications of the junction, transition or the hybrid integration of Industry 4.0 and 5.0.

A compelling analysis consists in discovering the advantages and disadvantages of adopting Industry 5.0. From a technological perspective, paper [17] states the relevance of integrating advanced technologies, such as real-time monitoring, to aid workers express their creative nature, while automation elements handle repetitive and mundane tasks, constructing a flexible operational process. This would reinforce the ideology of synergistic revolution, rather than interchangeable considerations.

Authors of paper [18] propose a comprehensive framework that introduces the conceptual foundation, an array of technological principles, areas of focus, levels of implementation and "triple bottom line" as key pillars for moving towards incorporation of Industry 5.0 mentality in industrial mediums. In the technological principles pillar, it is identified that collaboration, coordination, communication, automation, data analytics and identification shape an effective milieu for ensuring that disparate parts facilitate an optimal information exchange across various stakeholders and departments, while leveraging data to improve decision-making and operations.

As Industry 5.0 relies heavily on interoperability, for creating a responsive and interconnected system, exploring new technologies and industrial practices for building a cohesive, resilient and efficient ecosystem becomes adamant [19].

Scholarly study [20] observes a significant amount of limitations in terms of research efforts, from which it can be enumerated: scarcity concerning empirical studies, limited amount of systematic analysis, constrained range of focus for existing research, insufficient interdisciplinary approaches, rapid technological advancements and lack of resilient implications, which lead to gaps in view of research. A broader understanding of enabling technologies, architectures and methodologies is necessary to implement real-life use-cases, which support a sustainable embracement of this movement.

Moreover, human participation and automation balance persist the societal impact, prioritizing the organic intelligence of workers in addition to machine precision, as per [21].

OT-IT convergence, therefore, becomes paramount for attaining the goals proposed by the Industry 5.0 revolution, especially considering the intensification of digitalization efforts [22]. Disparate operational priorities between the two layers mark an important gap: the information technology layer focuses on data by leveraging its integrity, confidentiality and availability, whereas the operational sector values availability and reliability. From a technical perspective, the data model incompatibility is significant for the OT-IT convergence: OT data are isolated, uncorrelated and unstructured, while IT data are transactional and structured. This decoupling affirms the necessity of innovation to sustain information exchange between entities, alongside data correlation and accessibility. Paper [23] approaches an ontological solution, proposing a systemic methodology for data integration, targeting specifically IoT meshes.

The challenges of integrating the OT level are considerably exacerbated by its characteristic nature of critical importance for business operations, especially in the context of security and hyperscalers correlated to cloud and IIoT, confirming the data-driven essence of modern environments [24]. This involves a validated architecture for the operational layer constraints, which not focuses only on migration but integration, impacting coevality.

At the present time, the operational level benefits from the Open Platform Communication Unified Architecture (OPC UA). Although industrial equipments have majorly evolved in the direction of utilizing this consecrated client-server protocol for the operational level integration with designated digitalization technologies (for example, Digital Twins - DT) [25], [26], [27], a tendency towards asynchronous messaging models, such as Publish-Subscribe [28], is signaled, Additionally, the amount of independent communication protocols, of legacy systems and proprietary SCADA systems raises a series of concerns.

The research paper [29] shows that, in spite of the standardized and reliable nature of OPC UA, the intrinsic constraints pertaining to the outdated equipment obstruct viable resolves for integration, suggesting that fully customized solutions which delegate flexibility as a congruent enabler in this contemporary context.

At the IT layer, the possibilities of interoperability are reduced, respectively, solutions are based on file-based data exchanges [30], database level access [31] or Application Programmable Interface (API) integration [32]. More modern systems are open to standardized protocols considering Message Queuing Telemetry Transport (MQTT) and Advanced Message Queuing Protocol (AMQP) at the application level. However, some legacy systems are completely segregated in their current functioning.

The integration of traditional legacy systems into modern technological infrastructures generates a multitude of complex challenges that require a methodical and strategic approach to ensure a smooth and effective digital transformation process [33].

The principles of Industry 5.0 emphasize the importance of human-centricity, sustainability, and resilience. To align with these, it is crucial to integrate and ensure smooth cooperation between OT and IT. This harmonization is essential for efficient data movement and maintaining operational efficacy amidst complex, fast-paced changes in technology and paradigms. Challenges such as incompatibility and the variety of data formats can impede effective information exchange, highlighting the contradictions between numerous entities, as noted in studies [34] and [35].

The study [36] addresses a case study highlighting Asset Administration Shells (AAS) as key enablers of I5.0 and focuses on the challenges of integrating antiquated devices, where legacy systems' deficiencies in data structures and interfaces increase complexity, form data silos, and separate departments, while also focusing on the importance of a systematically coordinated database; Meanwhile, the manuscript [37] acknowledges that legacy systems create difficulties with standardized data formats and interfaces, thus impeding the development of an interoperable and operationally reliant ecosystem.

On the topic of data exchange, isolation between the two layers, namely OT and IT, promotes gaps in the efficiency of operational processes, as well as decisional ones. Information requires standardization for enhancing unobstructed aggregation and exchange in heterogeneous landscapes [38]. Thus, the concept of single-source-of-truth becomes auspicious for the construction of a unified data structure, resolving inconsistency and duplicity between infrastructural levels [39]. Paper [40] utilizes a virtual unified namespace for data networking founded on an ISA-95 standardized structure, leveraging the AAS concept.

As modernization strategies for legacy systems confine a particular area of interest, [41] examines strategical proposals, while suggesting a habitual resistance to change caused by the inherently integral characteristic of these systems. One fascinating discussion points to disruption of ongoing operations, which ultimately justifies the vacillation in terms of adopting new technologies and methodologies. Considering this, it argues that modernization efforts are regressing. Besides, to ensure an optimal exchange between adoption and integration, assessing the impact for the company and involved stakeholders, an effective cost analysis should be performed, as costs represent a main driver of stagnation.

Paper [42] outlines the importance of a conceptual framework for improving legacy systems, emphasizing that the lack of a well-defined approach will exacerbate the difficulties associated with merging obsolete systems with current technology. This complexity could hinder organizations in effectively handling intricate transformation demands, both theoretically and practically.

Manuscript [43] highlights the critical issue of scalability within legacy systems, which rely on outdated technology stacks that hinder efficient scalability. It emphasizes the importance of transitioning to modern data architectures to handle increasing data volumes and improve the experience of the user. The work advocates for integrating scalability into enterprise architecture strategies to enhance performance and support sustainable development efforts, additionally underlining the criticality of data associated with scalability and overall accessibility.

Moreover, older applications have a monolithic approach in determining their software architecture, providing additional efforts in relation to implementing a viable design for an enterprise-wide environ which scales alongside business requirements, as opposed to a microservices based method. Their tightly-coupled and interdependent resources pose a notable deterrent correlated to integration and interoperability efforts, as their expansion is limited and addition of modules can require scaling for the entirety of the system [44]. Authors of article [45] state that organizations moved in the direction of modernizing their outdated computing system by decomposing monolithic application in microservices, although a series of difficulties arise: high complexity, microservices identification, independent deployment, code decomposition, data management and storage, communication between independently decomposed modules.

Furthermore, research work [46] opens up avenues for data-centric processes, focusing on data decomposition in a microservices-based migration strategy. The authors argue that database and schema analysis marks a shift from traditional methods that place emphasis on the functional aspects. Their methodology acts in opposition to the aforementioned point, focusing on clustering data and structuring mappings for a data-driven approach. The establishment of clearly delineated boundaries and the assignment of specific responsibilities can significantly contribute to the overall effectiveness and efficiency of organizational structures and interpersonal relationships within various organizational contexts.

Among these lines, one prominent discussion is based on data consistency. This aspect is tackled in paper [47], discussion the real implications of the two different types of architectures and their trade-offs. It is identified that in a microservices-based approach, as each service manages their individual information sources, it is probable to lead to data integrity issues. The authors propose a series of potential strategies, which include techniques such as data replication in a shared repository, though it might lead to tight coupling.

The ontology learning framework discussed in article [48] emphasizes the challenges of integrating legacy ERP systems, criticizing traditional methods for their inflexibility. The article argues that to meet the evolving demands of complex and dynamic environments, integration approaches must prioritize adaptability and personalization to effectively integrate system components.

Manuscript [49] refines a strategic methodological recommendation, which involves a four-step approach for a governed perspective. The steps consist of assessing the company's integration objectives in alignment with business needs, documenting the resulting frameworks for further evaluations, proposing a significant role for IT in executive processes, leveraging collaboration for interoperability and integration governance. This allocates a primary role for integration governance at organizational level. Not only does this support a shift from the previously isolated solutions but also encourages a new direction for interconnection, coevality, interoperability and communication.

Research study [50] was conducted in the Insurance field, modernizing legacy software by utilizing middleware platforms and highlighting their role on this type of orchestration. It was observed that 70% of budget allocation is consumed on maintenance for IT legacy systems. Adopting middleware solutions serves as a bridge between legacy and modern solutions, promoting characteristics such as protocol translations, service orchestration, data transformation and of highest importance, system functionality and performance improvements.

In addition, paper [51] supports middleware adoption for legacy system integration with consideration to extension of operational life by allowing interfacing with contemporary technologies, as well as increased flexibility, which allows for new functionalities, while not soliciting the entirety of the legacy system. There is also a benefit in terms of risk mitigation, as destabilization is improbable due to confinement of legacy modules and provides simplified maintenance and development. As the middleware can serve as a centralized hub for clients, it additionally broadens the usability of the system, with no compromise of jeopardizing the antiquated solution. The authors argue that adopting this kind of strategy conjointly traverses to increased innovation and improved team morale.

According to the relevant literature [52], the identified challenges surpass mere technical limitations and also include notable shortcomings in informational understanding, knowledge and documentation.

The paper [53] discusses the challenges posed by vendor lock-in, particularly in cloud computing. Vendor lock-in limits development, integration, and interoperability by making clients dependent on specific vendors for products and upgrades. This dependency can lead to obsolescence and lack of innovation, while migrating away from a vendor can be costly and disruptive to business processes. Thereby, the manuscript offers an analysis of vendor lock-in's impact, concluding that reliance on particular providers complicates transitioning to alternative solutions technologically, operationally, and financially. Organizations face increased complexity in managing their infrastructures, highlighting the need for open-source solutions.

Ongoing analyses of advancements within the actual industrial sphere rely largely on collaborations between academia and industry. Through such alliances, practical, market-ready innovations are propelled forward, all while bolstering the current body of knowledge.

III. SOLUTION DEVELOPMENT

This section of the paper will cover the theoretical and tangible implementation of the proposed solution, with specific regard to IT-level integration methodologies, in a practical manner, while additionally depicting the resulting architectural framework. Particular independent elements for the integration layer will be detailed in three subsections. All subsequent activities were carried out for a concrete proof-of-concept use case within the Production domain related to the water industry sector, therefore utilizing real-life data. The conducted research serves as an extension of paper [14], broadening the functionality, understanding and implications of the initial framework.

The proposed scenario utilizes three distinct broadly used methods for data transfer, specifically file data transfer, direct database connection and API endpoints for an empirical data format standardization in the IT-level context. The proposal covers a simulative integration with OT-level data sources for uniformization and consumption, thus maintaining the ideology of inter-level convergence by utilizing Modbus TPC/IP and OPC UA. Data sources in the IT domain pertain to the same legacy application, as the scope is represented by integrability in the context of Node-RED, rather than focusing on attaining particular data generators for this experiment. Consequently, the systems have to be considered independent for their purpose, thus resulting in five entities for the objective of this project.

Therefore, development focuses on an empirical design for co-existence, harmonization and reduction of implementation complexity, introducing the real-life possibility for future extensions with an additional Geographic Information System (GIS) or other widely-utilized technologies from the industrial spectrum.

The primary objectives of this research implementation are the following:

- Developing an incipient viable architectural framework that uses Node-RED as middleware not only to enhance the functionality of the legacy system, as per [14], but also to promote an interoperable ecosystem capable of adjusting to the needs of digitalization in the context of convergence in OT-IT.

- Evaluating the effectiveness of the proposed conjoined infrastructure through the proof-of-concept use case and understanding its implications.

As a main focal point, this experimental case study will aid in addressing the following questions:

1. What are the identified key opportunities for OT-IT convergence in this specific context?

2. Can Node-RED be effectively implemented as middleware to fit the criteria established in scholarly literature?

3. What improvements can be observed after integrating Node-RED?

4. What benefit will it introduce to future-proof internal processes and ensure a single-source-of-truth (SSOT) for data acquisition in upcoming implementations?

Therefore, the academic discourse is centered around the capability of Node-RED to adjust and promote a strongly decoupled, yet centralized, intermediary Processing and Integration Layer for OT-IT convergence, as well as on data acquisition and standardization for comparison between integrability utilizing point-to-point (P2P) connections and SSOT.

Consequently, the interest is maintained on constructing a viable architecture to support the emergent I5.0 paradigm, in the context of intensive digitalization.

Thus, the three major points of interest in the experiment are drawn from the dissimilar integration patterns commonly utilized at the IT-level, specifically:

1. Integration of Excel file for manual data extraction.
2. Direct integration of an Oracle database.
3. Integration based on API endpoints for data injection.

Subsequently, the OT level integration will be addressed utilizing a Modbus TCP/IP simulator and KepServerEX OPC UA software.

Fig. 1 depicts the architecture designed for the proposed scenarios, examining the potential for IT-OT convergence through the use of the referenced framework design. The compatibility of integration with Node-RED at the OT layer has been thoroughly analyzed in previous academic work [54].

The illustration provides a comprehensive graphical representation of various components that are integral to the overarching framework, with Node-RED emerging as the pivotal element that facilitates interoperability between disparate systems. Serving as the selected middleware platform, Node-RED plays a crucial role in bridging the two enterprise levels.

In the proposed architectural design, among the OT and IT sections, the following entities can be particularly identified: the Processing and Integration Layer, the Virtualization Layer and the Reporting Layer. Hence, the final solution promotes a skeleton that interlocks the operational and informational data sources and targets, independent of standards and protocols, and the aforementioned standardized layers for digitalization practices.

As the two levels introduce the five practical data sources, the Reporting layer mediates the data consumption for user involvement, thereby designating the target for this particular scenario.

In upcoming paragraphs, the tangible implementation is tackled following a set of predefined aspects, which will be used to attest the viability in the Discussion chapter of the paper. To ensure seamless integration, proper scaling and OT-IT convergence for additive operational processes in future digital transformation efforts, the systematic steps engaged are as follows: integration requirement assessment, data mapping and standardization, automation of data extraction, data transformation and loading, validation and quality assurance. The planning phase becomes adamant for consistency in the implementation phases, as the rigorous delineation provided a compelling skeleton for re-usability, scalability and reducing overall complexity.

Data mapping and standardization is a crucial phase that will not only lay the groundwork for the existing integration architectural design but will also serve as a foundation for future methodologies. From this perspective, the depiction shown in Fig. 2 emphasizes an exemplified variant of the selected structure for data standardization, which will apply

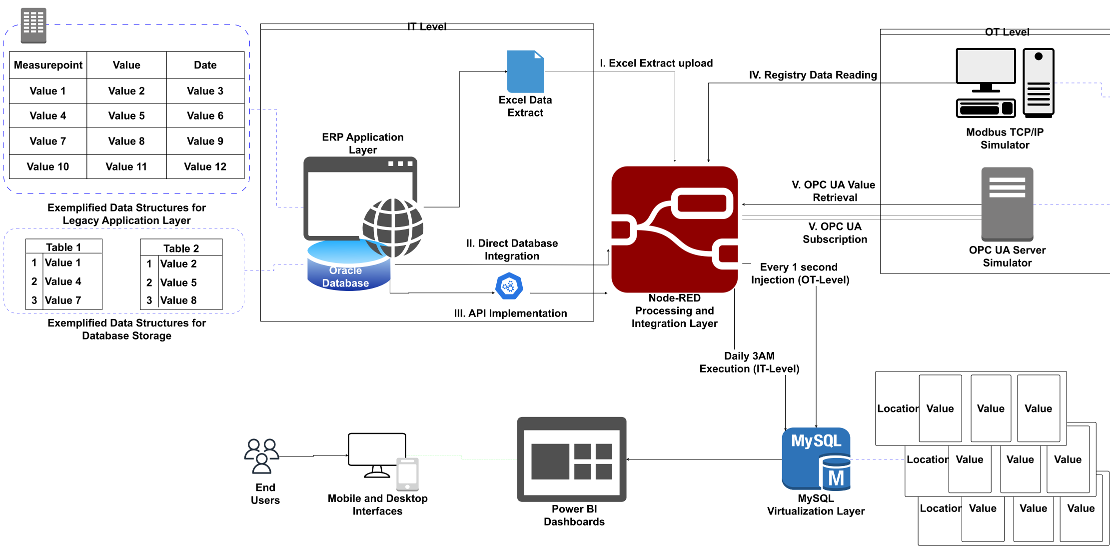

FIGURE 1. Case study architectural proposal.

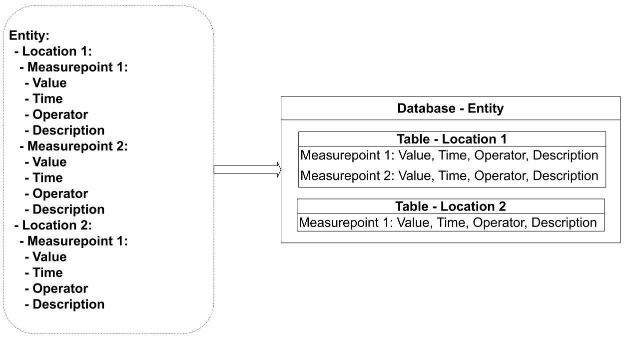

FIGURE 2. Virtual unified data structure.

to the three scenarios explained below and will extend to the simulative data producers.

The selected structure presents a substantial characteristic benefit; particularly, it translates effectively to MQTT or AMQP topics, aiding in protocol adoption, supporting reutilization. In addition, its simplicity stems reduction of complexity for heterogeneous data sources, providing a solid foundation for unified information, as it can be extended and adapted depending on particular necessities. This implies complete independence of data producer, but reliance on the Integration layer.

The Reporting layer, which mainly constitutes a consumer in the described scenario, is purposely implemented to utilize exclusively only the dynamically generated in a compelling visual, to provide a final overlook on the attainability of a unified repository, where all sources are independent, but correlated. The visualization is constructed on an aggregation of the entities, presenting the latest value read, a historical evolution for the locations, the total sum for all cumulated distribution points and the highest value of the measurement depending on the selected timeline, per location.

A. FILE SYSTEM INTEGRATION

Considering data file exchange as a consecrated methodology for transfer and migration, the capacity of Node-RED to integrate this kind of mechanism was evident. As major software still operates on this kind of approach on both levels, providing an interoperable solution for managing this kind of transfer marks an interest point for synergic relationships between inter-level entities. Node-RED presents the base capacity of integrating file system information in an out-of-the-box manner, thus the implementation could be developed further.

The files are manually uploaded to a common folder via a manual activity, directly from the source system. This triggers the integration flow and further processing via utilization of an event watch to monitor folder and file changes. Moreover, this points towards a contemporary approach of an event-driven medium, supporting responsiveness. Albeit the optimization for modern practices, a standard scheduled injection can still be employed to ensure common functionality across flows.

To further elaborate on the logical execution of the processing framework, the subsequent phase entails the reading and structuring of data sourced in a comma-separated value (CSV) file format. Data extraction is executed via a designated out-of-the-box node available in Node-RED for reading files. It is further transformed into accepted SQL standards. This transformation is crucial because it enables the seamless integration and manipulation of data within relational database systems.

The method of data formatting and the creation of SQL statements is performed in a highly flexible and responsive way, with no hard-coded elements regarding table names or fields. The platform processes the input utilizing JavaScript functions and creates a Local Flow Variable for the JavaScript object. This object is then transformed into the required

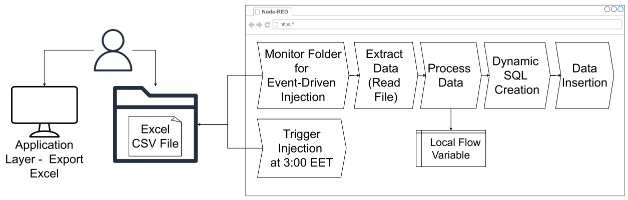

FIGURE 3. **Processing logic for excel file extraction.**

SQL Statement for Data Insertion, based exclusively on the acquired data.

This adaptability is essential, as it enables the development of a unified information framework, which then serves as a definitive single-source-of-truth for all downstream consumers. Ensuring that data are carefully structured, as shown in Fig. 2, a strong foundation is established, which not only improves integrity, but also facilitates access and usability between various applications and stakeholders.

Moreover, the functional aspect is structured in separated components, via sub-processes, thus associating particular steps of the logical process with particular acquisition phases, as previously mentioned. This modularization is essential for the re-usage of components, reducing development time, as in the constructed experiment the modules were implemented only once.

Fig. 3 illustrates the core processing logic integral to this procedure, emphasizing the flow of data described above. This visual representation serves to clarify the intricate pathways through which information is processed, delineating the various components involved.

In this schematic, the user is presented as part of the process, considering the role of personnel, specifically to ensure the continuous flow of data through manual activities, which trigger the Node-RED integration. The manual activities are strictly correlated to the legacy system and do not interact in any direct manner with Node-RED, as the non-automated mechanism of file extraction is decoupled from the automated execution logic. The implications of this will be discussed further in the Discussion section of this paper.

B. DIRECT DATABASE CONNECTION

For the second implementation proposal, a direct database connection was selected, to affirm the adaptability of Node-RED for diverse sources. The extraction and transformation process was conducted in a similar manner to the first method used, attesting the reutilization of components and sub-processes.

The flow is started using scheduled triggers. Similar to the first scenario, one element that needs to be independent of the rest is the connection manner. In this case, the connection to the data source is established through an Oracle Database pre-existing node. The acquired data are managed in the same manner, converting it to a local flow context JavaScript object, and SELECT queries are designed utilizing the dynamic recognition system. There is a notable reduction in the number of hard-coded components, allowing for successful re-use of the created decoupled elements. This is visible in Fig. 4, underlining the ease of customization in the proposed approach, while maintaining the same constituents of the processing logic.

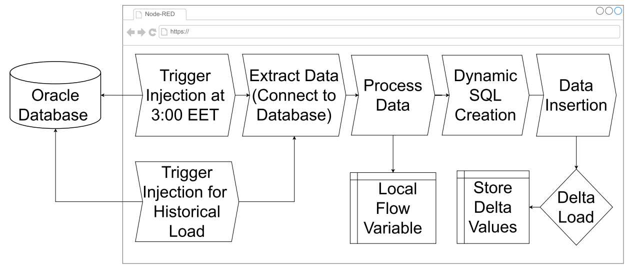

FIGURE 4. **Processing logic for direct database connection.**

C. DIRECT API INTEGRATION

The foundation of the flow hinges on the network of interconnected nodes that collaboratively support the seamless and efficient transfer of data from the Oracle Database through a custom-built Python REST API endpoint into the unified virtual namespace. The implementation of the API endpoint for database extraction was implemented utilizing the FastAPI framework for Python. Although the specificity of the solution, the flow is still independent of the source, in this case the self-developed API. The design was created for extensibility, scalability and reusability, as proven by the refined skeleton of the flow.

The integration flow is triggered by the injection node, configured with scheduling functionality, which afterwards utilizes a specialized input node for HTTP connection, configured with GET operation.

It is imperative to note that authentication and authorization must be employed to ensure secure access to the APIs. This involves the implementation of the OAuth 2.0 protocol, which facilitates the acquisition of access tokens necessary for API interaction. The flow includes configurations dedicated to managing the authentication process, ensuring that all data extractions and insertions are conducted in a secure and compliant manner. Following the authentication method, connection is established through an HTTP node with GET operation configured to access the required endpoint.

This specific use case involved the conversion of the API response body to a JavaScript object, alongside the established dynamic SQL statement node. Upon successful transformation and SQL creation, the process advances to the core functionality of inserting data into the Virtualization layer, represented by MySQL.

Moreover, for redundancy reasons, as well as unifying the virtualized data under the constraining standardization for this type of integration, data is stored under the MySQL tables utilizing the same dynamic data insertion process component as for the aforementioned use cases.

Fig. 5 illustrates the Node-RED process for this approach. Remarkably, the notable differences are the connection

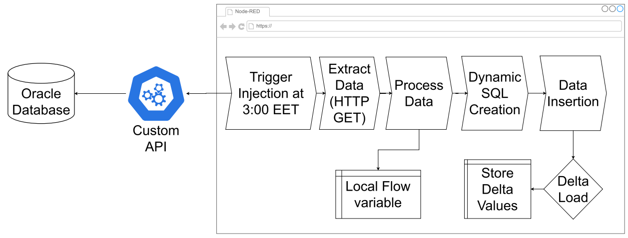

FIGURE 5. Processing Logic for API operations.

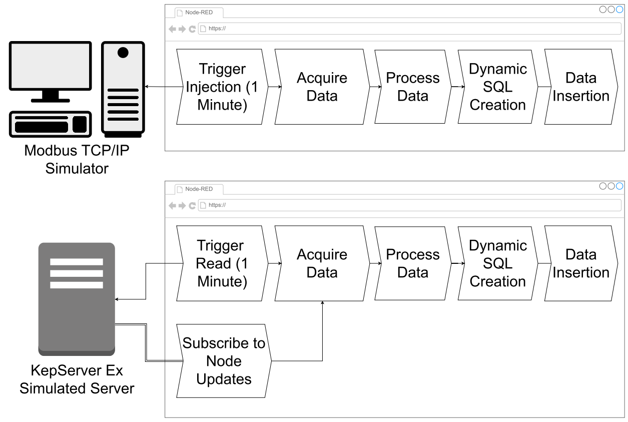

FIGURE 6. Processing Logic for OT-Level Software.

methods throughout the scenarios, underlining the versatility of the chosen medium.

D. OT-LEVEL SOFTWARE INTEGRATION

To evaluate the feasibility of the proposed unified framework at the operational level, simulative software has been used to test integration with Modbus TCP/IP, and KepServerEX has been chosen for the experimental phase of this integration with OPC UA. As the execution logic of the Node-RED flows consists of reusable components, the processing behind it is similar to the previously presented computational units. This method proves to be highly flexible in handling various data sources, emphasizing the advantage of employing a middleware solution as a processing layer for standardizing and correlating data prior to integration and convergence.

Therefore, Fig. 6 underlines the integration method for Modbus and OPC UA:

In one scenario, the traditional polling method was utilized for the OPC UA data source. In contrast, the other case involves subscribing to the server, resulting in it delivering updates to the client. Both scenarios connect to the source via the same node, differing only in configuration, not in the input nodes. Thus, it will be regarded as singular connectivity point, but will be tested separately for both premises.

For the connectivity with the Modbus simulator, a Modbus Flex Getter node was introduced to create the integration point. Data is acquired from the holding registry 40013.

Details about the initial data formats are illustrated in Fig. 1. Once the connection is successfully established, the data undergoes processing with the previously mentioned algorithm that can identify and align it to a standardized target data format. Dynamic SQL creation is performed based on the extracted and processed data, resulting in the execution of the same batch data insertion into the virtualization layer.

IV. RESULTS AND DISCUSSIONS

As this paper is constructed as an extension to paper [14], development and test scenarios were conducted in the water industry sector, utilizing prerequisites and findings from the aforementioned scholarly work.

The overall architecture was developed bearing in mind prevalent shortcomings identified in enterprise infrastructure ecosystems, particularly interconnection hardships of OT-IT levels due to lack of flexibility, scalability and compatibility, alongside data inconsistency, reliability, availability and standardization.

For the testing methodology, the data acquisition phase was executed in separate installments for each of the IT-level data sources, to assess the impact of each individual when using the proposed dynamic components in Node-RED, while also evaluating the accuracy and consistency data. This step had a 100% success rate, as all information was attributed to the correct entity in the standardization layer and maintained the integrity and accuracy of data, while enhancing accessibility. Therefore, the proposed modularization of implemented elements attests to the possible re-utilization and the dynamic aspect in relation to varying selected data.

For the OT-level sources, triggers were conducted in a simulated, controlled environment. The objective is to integrate and present information from different formats in a single cohesive view. This approach aids in the analysis and understanding of the suitability of our solution in the context of data which originates from various systems, ensuring compatibility and coherence despite the differences in their native formats.

A key principle in the proposed design is the breaking down of silos through the conjunction of the operational and informational domains, as the rapid introduction of digitalization instruments fundaments a data-driven decision-making organizational process and intensifies the requirements for a unified data governance.

The implementation focuses on a layered integration paradigm utilizing an open-source middleware solution as the leading actor for dynamic processing and transformation, whereas the standardized data model mandates a centralized data governance layer for virtual unification of disparate-level data sources. Thereafter, the finalized solution presents three decoupled layers, excluding the designated OT and IT levels:

- Processing and Integration Layer
- Virtualization Layer
- Reporting Layer

The approached model ensures a functional environment governed centrally consolidated by a unique data repository. An additional crucial aspect is represented by the modularity of the overall architecture and the Node-RED integration flows attest to evolving adaptability, especially in fast-growing modern enterprise environments.

The business scenario was discussed in the context of uncorrelated data from the operational and informational areas of the organization, introducing the necessity of inter-department collaboration. Applying the methodology analyzed to the specific scenario, in relation to common protocols and communication mechanisms at the IT level, demonstrated a high integrability rate, as Node-RED was successful in accommodating the requirements of each data transfer method. Practically, it has the potential to reconcile overlapping development efforts by enabling reutilization of components in a modular manner.

Likewise, data redundancy has been reduced through the standardization process, as newly acquired data is inserted, whereas changed data is updated, therefore ensuring a functional background for decreasing resource consumption in terms of storage functionality. It is requisite to mention the dynamic processing aspect of the integration, as all datum is processed utilizing modular components that gradually adapt SQL statement in a unified way, depending on the calling process, thereby scaling the system requires minimal development efforts and no organizational disruptions.

Equations (1) and (2) refer to calculations for the total number of ecosystem connections in an interconnected mesh utilizing our proposed methodology with a single-source-of-truth (C_{SSOT}) and a standard rudimentary point-to-point (C_{P2P}) approach. Equation (1) is the sum of all sources, targets and the proposed unification layer, whereas Equation (2) is represented by the multiplication of sources and targets.

$$C_{SSOT} = Sources + Targets + UnifiedLayer. \tag{1}$$

$$C_{P2P} = Sources * Targets. \tag{2}$$

The calculus for the reduction of linear complexity ($C_{reduced}$) is determined using equation (3), where the number of SSOT connections (1) is subtracted from the P2P connections (2), divided by total number of P2P connections and multiplied by 100.

$$C_{reduced} = \frac{(C_{P2P} - C_{SSOT})}{C_{P2P}} * 100. \tag{3}$$

Furthermore, the analyzed methodology has the potential to decrease the complexity of linear connections. In the experimental scenario, considering the five sources and one technical consumer of data, the proposed SSOT introduces a small overhead, resulting in 7 total connections (1). Excluding compatibility issues from this calculation, for a direct point-to-point architecture, the number of connections would cumulate to 5 (2). This number exponentially increases with additive connections, defining an unmanageable environment, raising complexity and decreasing transparency and efficiency. Hence, for a large-scale environment with 100 data producers and 100 consumers, defining a fully interoperable setting, connections for an SSOT scenario would be 201,

TABLE 1. Equation calculus for various source and target scenarios.

Sources&Targets	5	10	50	100
C_{SSOT}	11	21	101	201
C_{P2P}	25	100	2500	10000
$C_{reduced}$	56%	79%	95.96%	97.99%

while for a P2P frame it would reach 10000 links. Therefore, in a hypothetical fully-connected mesh, the complexity would be reduced by 97.99% (3). Table 1 refers to hypothetical scenarios, including the one highlighted above regarding the 97.99% reducing of complexity utilizing our methodology for constructing the framework:

Suggesting quantitative assessments, an analysis was conducted for the latency and throughput of Modbus TCP/IP and OPC UA protocols, as these define more restrictive real-time requirements as opposed to the IT-level integration. It was executed in a controlled environment by running load tests on the end-to-end flows, computing over multiple 60-second observation windows.

The average latency across all received messages is calculated using:

$$\bar{L} = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{4}$$

where:

- L_i — latency of the i^{th} message (in milliseconds)
- n — total number of messages received in the observation window

The variation of latency values is measured as follows:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(L_i - \bar{L})^2} \tag{5}$$

where:

- σ — standard deviation of latency
- $\bar{L}$ — mean latency

The 95^{th} percentile latency represents the latency value below which 95% of all latency samples fall:

$$L_{95} = L_{\lceil 0.95 \cdot n \rceil} \tag{6}$$

where:

- L_{95} — 95th percentile latency
- L_i — latency samples sorted in ascending order

The throughput in messages per second is defined as:

$$T_{\text{msg/s}} = \frac{n}{T} \tag{7}$$

where:

- $T_{\text{msg/s}}$ — throughput in messages per second
- n — number of messages processed during the window
- T — duration of the observation window (in seconds, here $T = 60$)

Table 2 confines the metrics obtained during load testing phases.

TABLE 2. Latency and throughput for real-time constraints.

	Mean Latency (ms)	Latency Variation (ms)	95^{th} Percentile Latency (ms)	Throughput (msg/s)
OPC UA - Read (every 500 milliseconds)	15.2	5.39	21	9.21
OPC UA - Subscribe	8.25	1.55	11	4
Modbus TCP /IP (every 500 milliseconds)	45.86	7.67	57	9.18

OPC UA in a Subscription scenario exhibited superior performance with a mean latency of 8.25 ms ($\sigma = 1.55$ ms, $L_{95} \approx 11$ ms at $T_{\text{msg/s}} = 4$ msg/s), indicating minimal delays and a low latency for most transmissions - this supports a successful use in real-time contexts for an end-to-end processing flow, considering the Subscribe mechanism from OPC UA. Additionally, the implications of efficiency are raised by the event-driven nature of this use-case, but supporting the required typical requirements of assessing our framework proposal in a successful manner.

OPC UA using a Read node presented intermediate results: mean latency value was 15.2 ms, $\sigma = 5.39$ ms, $L_{95} \approx 21$ ms, $T_{\text{msg/s}} = 9.21$ msg/s. The moderate performance confines still well-tolerated values for multiple industrially-specific activities, such as trending or condition monitor, fulfilling the premise of integrability and data correlation.

By contrast, the Modbus simulation demonstrated greater variability (mean 45.86 ms, σ z 7.67 ms, $L_{95} \approx 57$ ms, $T_{\text{msg/s}} = 9.18$ msg/s). Given Modbus TCP/IP and the characteristics of the load testing—where the registry was accessed every 500 milliseconds—it suggests that queuing saturation is a major contributor to the delay. Additionally, the processing of each request, along with protocol overhead and network effects, are likely significant in the analysis of the results. Importantly, Modbus shows considerably less capacity reserve and is therefore more prone to a superlinear increase in latency as utilization rises.

Thereafter, considering the coveted integrability factor, Modbus and OPC UA can be integrated successfully in our framework, supporting latency-sensitive applications; borderline real-time exchange for Modbus with queuing saturation control can be incorporated to facilitate data exchange for less time-constraining processes. This assessment supports the viability of adapting the more intense prerequisites of operating industrial level with the informational level for a single-source-of-truth utilizing our proposed approach.

Moreover, structuring information in a common format through standardization permits inter-level correlation of data. Therefore, the centralized virtualization actor serves as a unified single access point for data consumption, improving overall integrity for cross-domain reporting and introducing a high-availability layer for data consumption.

In addition to scalability and reduced complexity, the risk of inconsistencies increases with the number of P2P sources. In the exposed scenario, the data maintained a consistent structure and quality throughout the extraction, transformation and loading (ETL) phases. The centralized repository delivers a single touch-point for information as for the Reporting Layer, hence diminishing access time for cross-domain utilization in the information and operational sectors. This resulted in a universal reporting page indifferent of source or acquisition layer. Fig. 7 represents the reporting page resulting from the development and research efforts. The implications of this introduce responsiveness and efficiency in the decision-making process and regulatory compliance via consistent taxonomies.

Upon analyzing the obtained outcomes and their implications, the open-source Node-RED middleware constitutes a strong integration choice for legacy systems and disparate data sources due to its scalability, flexibility, customizability, reusability, and complex visual programming interface. As requirements evolve, enterprise landscapes often need an adaptable and customizable landscape that adheres to a business critical environment. Node-RED allows for easy creation and modification of data flows, enabling seamless incorporation of new data sources or adjustments to existing workflows without extensive reconfiguration, underlining a superior digitalization strategy, especially for OT-IT convergence and interoperability, while maintaining a low-cost budget.

Existing traditional architectures entail a series of disproportionate disadvantages, which ultimately consist of complexity and scalability issues, requiring a simpler model capable of translating these intricacies into base functionalities [55].

As variety grows in terms of the technology repertoire, the high-level needed for personification ends in incompleteness or fragmentation, which ultimately leads to the corroboration of recurring challenges for development [56], hindering efforts of adoption and modernization. The proposed framework aligns with the baseline concepts for promoting a unified environment that offers a common platform for protocol translation, data acquisition and pre-processing, additionally playing into the role of integration layer. Moreover, the adamant requirements of interoperability, between legacy systems, contemporary ones and specialized industrial protocols, pose a problematic emblem in the industrial context, limiting options for successful inter-level communication [57]; therefore, the selection of a low-code middleware confines a favorable medium for rapid deployments [58].

As incremental additions can be made depending on growing needs of business without disrupting the ongoing process flows, it aligns with practical migration gaps identified by pertinent literature. Although standardization becomes a desired state concerning breaking down silos and

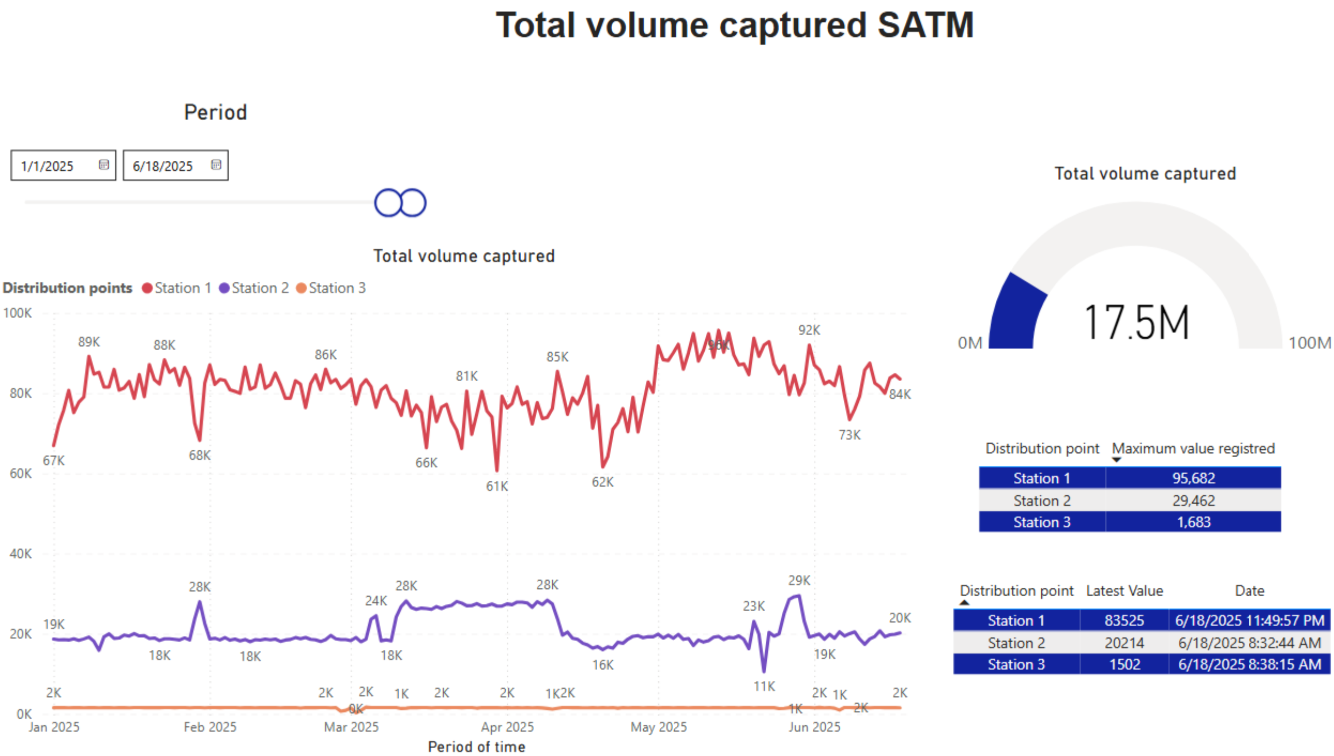

FIGURE 7. **Resulting Reporting Page.**

correlating inter-level information [59], attributing value and context to it, an agile concept remains adamant for catering to individual needs identified in companies [60].

In addition, as industries move forward, costs define a priority concern in the adoption tentative, paving the way toward a successful implementation; therefore, it is supporting an ideology where, although sectors move forward in a technology-driven way, it should maintain a beneficial aspect for the cost-effectiveness [61].

Real-life commercial solutions associated with Industry 4.0 are systematically transforming traditional capital expenditures into ongoing subscription-based service frameworks. Therefore, the financial responsibility is shifted from isolated acquisitions to enduring operational commitments, which escalates long-term cost structures, constrains budgetary flexibility, and necessitates more rigorous lifecycle and vendor-risk management from enterprises. Adoption of open-source frameworks can lead to potential benefits related to cost-savings, as the licensing fees are excluded from calculations, whereas operational and maintenance costs depend on the internal or cloud infrastructure selected and can be scaled depending on needs without overhead fees for usage.

As debated in this manuscript, one of the prevalent cases remarked is integrability of legacy systems: focus on solutions that have an accessible interface is recommended as legacy systems sometimes require greater degrees of freedom and the ability to generate their own interoperability solutions. In certain situations, the existing frameworks, do not cover the general needs in terms of specificity for majority of use cases that a company might require. It leads toward a sustainable result, as the same framework can be utilized in spite of the integration scenario, allowing integrability, interoperability and processing, in a single unit, independent of the sources and targets, without additional costs or introduction of complementary systems to fulfill requirements.

When it comes to shifting the paradigm from the I4.0 automation needs to the pillars of I5.0, the need to orient solutions towards resilience, especially in critical infrastructures (i.e. solutions that are fully available, with the in-house possibility of rapid remediation and modification) becomes adamant to ensure a drastic benefit for companies that seek the adoption of Industry 5.0. Therefore, these changes bring financial benefits through sustainability and resilience, alongside low investment fees. The technology proposed in the solution enables SSOT, decoupled entities, informed system operation, easy and complete implementation of an efficient solution, pointing toward financial benefits on the long term.

To conclude the Discussions section with, this kind of proven adaptability refines integration by mediating data processing and enhancing data quality through cleaning and transforming raw output from sources before they reach modern applications, thereby ensuring that only relevant and accurate information is analyzed. Overall, Node-RED empowers organizations to effectively bridge the gap between informational and operational domains, facilitating a smoother transition into a data-driven future.

A. LIMITATIONS AND ASSUMPTIONS

Considering the conceptual and experimental state of this project, it is necessary to discuss relevant potential implications and assumptions regarding practical usability.

Among the primary concerns is the feasibility of ingestion of real-time data in the context of a centralized virtualization layer for the operational sector utilizing real-life data from regionally distributed industrial protocols and solution over a prolonged period of time. Although the prototype has proven successful in integrating disparate data acquisition methodologies and promoting a unified visualization on standardized data, the computational demands have to be tested in a demanding environment for the OT layer, particularly focusing on performance metrics for real-time processing.

Furthermore, in spite of the promising integration of an IT-Level legacy system, alongside the extended compatibility of OT-level protocols, the solution should be assessed in a tangible manner, defining key constraints and opportunities correlated to the defined prototype context. Likewise, the proposal must be field-validated for data format structuring and standardization.

Moreover, the experimental status of our methodology involves theoretical calculus and simulated data for a large-scale interoperable medium, which needs to be thoroughly assessed in future research direction to confirm the full potential of complexity reduction and inter-level data integrity.

The general consensus of the organization across the business and operational domains confines an additional aspect regarding the standardization and unification and requires specialized interpretations.

B. FUTURE DIRECTIONS

Considering the convergence aspect, future directions include introduction of a GIS system for data acquisition, data which can be utilized in the same context as the proposed solution. This integration would represent a state-of-the-art approach for OT-IT convergence and correlation considering data standardization and interoperability, especially taking into consideration digitalization efforts and introduction of IIoT for real-time data acquisition. This would introduce the necessity of assessing the compatibility of the for real-time data processing in a live deployment medium.

As development directions navigate towards Publish-Subscribe messaging, analyzing the proposed data standardization structure presents a significant potential in adaptive transfer of information, harmonizing structures. This sets the foundations for an Event-Driven Architecture (EDA) exploration for large-scale real-time environments.

Additionally, exploration of AI models could bear potential benefits in the area of extensive metadata management, predictive maintenance and anomaly detection for converged OT-IT infrastructures.

The conduct of an organizational case study based on resistance to change determined by the organizational level dependent on governance difficulties and cultural influence factors presents a compelling investigation on data standardization and unification initiatives.

Additionally, while it may not align with the theoretical and experimental boundaries of this particular paper, a full implementation and integration of our proposal in a practical setting within a company is anticipated for future investigation into the benefits realized by the completed solution, which will primarily concentrate on the Return on Investment (ROI) for the quantitative metrics of the results.

V. CONCLUSION

Industry 5.0 promotes a compelling mentality inclined to a human-centric, sustainable and resilient organizational strategy. As it is in its incipient phases, the spectrum of possibilities in terms of successful implementation for digital transformation is broad and extensive. Albeit the numerous digitalization instruments, their utilization for the scopes of I5.0 depends majorly on academic partnerships and thorough investigations for promoting an innovative and flexible landscape.

The case study proposes a compelling solution predicated on leveraging data standardization and a middleware solution to construct a viable architectural design, capable of adapting with growing business requirements. The OT-IT convergence aspect is carefully tackled under the umbrella of interoperability by utilizing integration patterns in accordance to current IT-Level mechanisms and OT-level simulated data producers through consecrated Modbus TCP/IP and OPC UA protocols.

A powerful middleware tool which can represent the Processing and Integration Layer is essential to confine an interoperable medium for ease of extensibility and adaptability in terms of source-target communication in a consistent tone. This becomes a requisite in an interconnected ecosystem because of differences in protocols and technology stacks that demand more development efforts when utilizing older integration methods, supporting compatibility. The proposal consisted of the open-source software Node-RED.

A virtual unified data namespace is recommended to introduce a layer of coherence, represented by the Virtualization Layer, which points toward a more consolidated decision-making process and breaks down silos for functional departments, while ensuring a single-source-of-truth for all company data. The structure selected for the dynamic data transformation translates to MQTT or AMQP messaging protocols, extending the theoretical functionality to asynchronous messaging for future implementations, highlighting the interest for an event-driven approach.

The experimental prototype implied successful composition of a highly available enterprise infrastructure, introducing a modular development environment for Node-RED flows, increasing compatibility between systems, transfer mechanisms and protocols, including a fully dynamic data acquisition and standardization phase. Scaling is decoupled and ensures that there are no organizational disruptions, while reducing the complexity of linear connections for P2P relations in a hypothetical large-scale context.

The data unification presented a series of benefits, such as reduction of redundancy, increased transparency, accessibility and consistency, as well as inter-level correlation. A crucial advantage of the single-source-of-truth is the high-availability for data consumption and the integral cross-domain reporting.

Although the study has proven to be an opportunity for development in the context of Industry 5.0, especially when analyzing pertinent contemporary literature, limitations are discussed to introduce new opportunities in this field of research.

As a result, related inquiries in this context include uncovering the benefits of architectural convergence related to addition of hardware and software technologies, along with assessing the practicality of this method in highly-demanding real-time mediums. Moreover, the extensibility towards an asynchronous event-driven architecture and adoption of modern protocols (MQTT, AMQP) bear potential benefits for the industrial sector. The introduction of AI-driven insights represents another key point in the direction of innovation.

In addition, the significant impact of general consensus and collaboration between business and operational functions related to standardization and unification can be discussed as a future outcome of this research.

To conclude with, the conducted research proposes an experimental approach, with real-life use cases, in the direction of I5.0, utilizing middleware technology and virtualization techniques for data uniformization from diverse designated IT-Level integration methodologies and simulative OT-level sources, pertaining to different levels of contemporary practices. Hence, the infrastructure framework utilizes a three dimensional solution introducing a Processing and Integration Layer, a Virtualization Layer and a Reporting Layer for leveraging data quality, accuracy, accessibility and transparency. The finalized solution supports informed decision-making processes for involved personnel, while converging the OT-IT domains in an open-source scalable, modular, dynamic, highly-customizable and flexible framework, with a low implementation and operational cost.

REFERENCES

[1] J. Alves, T. M. Lima, and P. D. Gaspar, "Is industry 5.0 a human-centred approach? A systematic review," *Processes*, vol. 11, no. 1, p. 193, Jan. 2023, doi: 10.3390/pr11010193.

[2] M. Iqbal, C. K. M. Lee, and J. Z. Ren, "Industry 5.0: From manufacturing industry to sustainable society," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage. (IEEM)*, Dec. 2022, pp. 1416–1421, doi: 10.1109/IEEM55944.2022.9989705.

[3] S. Grabowska, S. Saniuk, and B. Gajdzik, "Industry 5.0: Improving humanization and sustainability of industry 4.0," *Scientometrics*, vol. 127, no. 6, pp. 3117–3144, Jun. 2022, doi: 10.1007/s11192-022-04370-1.

[4] M. Ghobakhloo, M. Iranmanesh, M. F. Mubarak, M. Mubarik, A. Rejeb, and M. Nilashi, "Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values," *Sustain. Prod. Consumption*, vol. 33, pp. 716–737, Sep. 2022, doi: 10.1016/j.spc.2022.08.003.

[5] L. Salandri, G. L. Cascio Rizzo, A. Cozzolino, and P. De Giovanni, "Green practices and operational performance: The moderating role of agility," *J. Cleaner Prod.*, vol. 375, Nov. 2022, Art. no. 134091, doi: 10.1016/j.jclepro.2022.134091.

[6] J. Barata and I. Kayser, "Industry 5.0 – past, present, and near future," *Proc. Comput. Sci.*, vol. 219, pp. 778–788, Jan. 2023, doi: 10.1016/j.procs.2023.01.351.

[7] G. Murray, M. N. Johnstone, and C. Valli, "The convergence of IT and OT in critical infrastructure," in *Proc. 15th Austral. Inf. Secur. Manage. Conf.*, 2017, pp. 149–155, doi: 10.4225/75/5a84f7b595b4e.

[8] D. Berardi, F. Callegati, A. Giovine, A. Melis, M. Prandini, and L. Rinieri, "When operation technology meets information technology: Challenges and opportunities," *Future Internet*, vol. 15, no. 3, p. 95, Feb. 2023, doi: 10.3390/fi15030095.

[9] M. Felser, M. Rentschler, and O. Kleineberg, "Coexistence standardization of operation technology and information technology," *Proc. IEEE*, vol. 107, no. 6, pp. 962–976, Jun. 2019, doi: 10.1109/JPROC.2019.2901314.

[10] S. Rosenkranz, D. Staegemann, M. Volk, and K. Turowski, "Explaining the business-technological age of legacy information systems," *IEEE Access*, vol. 12, pp. 84579–84611, 2024, doi: 10.1109/ACCESS.2024.3414377.

[11] S. Terry and V. Chandrasekar, "Systems engineering barriers to legacy system evolution: Legacy system assessment," *Syst. Eng.*, vol. 28, no. 2, pp. 207–223, Oct. 2024, doi: 10.1002/sys.21788.

[12] S. Ponnusamy and D. Eswararaj, "Navigating the modernization of legacy applications and data: Effective strategies and best practices," *Asian J. Res. Comput. Sci.*, vol. 16, no. 4, pp. 239–256, Nov. 2023.

[13] S. Huang, B. Wang, X. Li, P. Zheng, D. Mourtzis, and L. Wang, "Industry 5.0 and society 5.0—Comparison, complementation and co-evolution," *J. Manuf. Syst.*, vol. 64, pp. 424–428, Jul. 2022, doi: 10.1016/j.jmsy.2022.07.010.

[14] I.-V. Nitulescu, A. Korodi, and D.-I. Curiac, "Contribution study for digital transformation in the context of legacy IT level asset management systems," in *Proc. 25th Int. Conf. Control Syst. Comput. Sci. (CSCS)*, Bucharest, Romania, May 2025, pp. 225–230.

[15] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and industry 5.0—Inception, conception and perception," *J. Manuf. Syst.*, vol. 61, pp. 530–535, Oct. 2021, doi: 10.1016/j.jmsy.2021.10.006.

[16] M. Golovianko, V. Terziyan, V. Branytskyi, and D. Malyk, "Industry 4.0 vs. industry 5.0: Co-existence, transition, or a hybrid," *Proc. Comput. Sci.*, vol. 217, pp. 102–113, Jan. 2023, doi: 10.1016/j.procs.2022.12.206.

[17] R. Wolniak, "Industry 5.0—Characteristic, main principles, advantages and disadvantages," *Sci. Papers Silesian Univ. Technol., Org. Manage. Ser.*, vol. 2023, no. 170, pp. 663–678, 2023, doi: 10.29119/1641-3466.2023.170.40.

[18] D. Ivanov, "The industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives," *Int. J. Prod. Res.*, vol. 61, no. 5, pp. 1683–1695, Sep. 2022, doi: 10.1080/00207543.2022.2118892.

[19] A. Adel, "Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas," *J. Cloud Comput.*, vol. 11, no. 1, pp. 1–15, Sep. 2022, doi: 10.1186/s13677-022-00314-5.

[20] G. K. Dua, "Advancements in industry 5.0: A descriptive analysis and future research directions," in *Strategies and Frameworks for Relearning in Organizations*. Hershey, PA, USA: ICI Global Scientific Publishing, Oct. 2024, pp. 243–264, doi: 10.4018/979-8-3693-6312-6.ch009.

[21] M. Khan, A. Haleem, and M. Javaid, "Changes and improvements in industry 5.0: A strategic approach to overcome the challenges of industry 4.0," *Green Technol. Sustainability*, vol. 1, no. 2, May 2023, Art. no. 100020.

[22] F. Folgado, D. Calderón, I. González, and A. Calderón, "Review of industry 4.0 from the perspective of automation and supervision systems: Definitions, architectures and recent trends," *Electronics*, vol. 13, no. 4, p. 782, Feb. 2024, doi: 10.3390/electronics13040782.

[23] K. Koorapati, R. Pandu, P. K. Ramesh, S. Veeraswamy, and U. Narasappa, "Towards a unified ontology for IoT fabric with SDDC," *J. King Saud Univ.-Comput. Inf. Sci.*, vol. 34, no. 8, pp. 6077–6091, Sep. 2022, doi: 10.1016/j.jksuci.2021.04.015.

[24] C. Perducat, D. C. Mazur, W. Mukai, S. N. Sandler, M. J. Anthony, and J. A. Mills, "Evolution and trends of cloud on industrial OT networks," *IEEE Open J. Ind. Appl.*, vol. 4, pp. 291–303, 2023, doi: 10.1109/OJIA.2023.3309669.

[25] A. Abdelsattar, E. J. Park, and A. Marzouk, "An OPC UA client/gateway-based digital twin architecture of a SCADA system with embedded system connections," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Sapporo, Japan, Jul. 2022, pp. 798–803.

[26] H. Lee, "Construction of an integrated platform for a smart factory cyber physical production system based on an OPC-UA linked digital twin," *J. Inst. Control, Robot. Syst.*, vol. 28, no. 8, pp. 768–772, Aug. 2022.

[27] V. Souza, R. Cruz, W. Silva, S. Lins, and V. Lucena, "A digital twin architecture based on the industrial Internet of Things technologies," in *Proc. IEEE Int. Conf. Consum. Electron.*, Jan. 2019, pp. 1–2, doi: 10.1109/ICCE.2019.8662081.

[28] A. Ioana and A. Korodi, "DDS and OPC UA protocol coexistence solution in real-time and industry 4.0 context using non-ideal infrastructure," *Sensors*, vol. 21, no. 22, p. 7760, Nov. 2021, doi: 10.3390/s21227760.

[29] R. Sujith, R. Ilayaraja, K. Durgadevi, N. Balaji, and A. Vignesh, "Seamless integration of legacy industrial systems with OPC UA for enhanced digital transformation," in *Proc. Int. Conf. Power, Energy, Control Transmiss. Syst. (ICPECTS)*, Oct. 2024, pp. 1–6, doi: 10.1109/icpects62210.2024.10780333.

[30] H. T. Wörden, F. Spreckelsen, S. Luther, U. Parlitz, and A. Schlemmer, "Mapping hierarchical file structures to semantic data models for efficient data integration into research data management systems," *Data*, vol. 9, no. 2, p. 24, Jan. 2024, doi: 10.3390/data9020024.

[31] C. Ma, "Data integration of legacy ERP system based on ontology learning from SQL Scripts," in *New Trends in Databases and Information Systems* (Communications in Computer and Information Science), vol. 1064. Cham, Switzerland: Springer, 2019, doi: 10.1007/978-3-030-30278-8_52.

[32] V. Kanvar, S. Tamilselvam, and K. N. Raghunath, "Enabling communication via APIs for mainframe applications," 2024, *arXiv:2408.04230*.

[33] Z. Irani, R. M. Abril, V. Weerakkody, A. Omar, and U. Sivarajah, "The impact of legacy systems on digital transformation in European public administration: Lesson learned from a multi case analysis," *Government Inf. Quart.*, vol. 40, no. 1, Jan. 2023, Art. no. 101784.

[34] A. Korodi, I.-V. Nitulescu, A.-A. Fülöp, V.-C. Vesa, P. Demian, R.-A. Braneci, and D. Popescu, "Integration of legacy industrial equipment in a building-management system industry 5.0 scenario," *Electronics*, vol. 13, no. 16, p. 3229, Aug. 2024, doi: 10.3390/electronics13163229.

[35] O. Givehchi, K. Landsdorf, P. Simoens, and A. W. Colombo, "Interoperability for industrial cyber-physical systems: An approach for legacy systems," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3370–3378, Dec. 2017, doi: 10.1109/TII.2017.2740434.

[36] A. Zielstorff, D. Schöttke, A. Hohenhövel, T. Kämpfe, S. Schäfer, and F. Schnicke, "Overcoming challenges in integrating legacy devices with asset administration shells—An OPC UA case study," in *Proc. 28th Int. Conf. Emerg. Technol. Factory Autom.*, Sep. 2023, pp. 1–8, doi: 10.1109/etfa54631.2023.10275536.

[37] A. Zielstorff, D. Schöttke, A. Hohenhövel, T. Kämpfe, S. Schäfer, and F. Schnicke, "Harmonizing heterogeneity: A novel architecture for legacy system integration with digital twins in industry 4.0," in *Proc. Int. Conf. Innov. Intell. Ind. Prod. Logistics*, Jan. 2023, pp. 68–87, doi: 10.1007/978-3-031-49339-3_5.

[38] P. Gujar, "Data standardization and interoperability," in *Data Usability in the Enterprise*. Berkeley, CA, USA: Apress, 2025, pp. 89–110, doi: 10.1007/979-8-8688-1183-8_4.

[39] C. Pang and D. Szafron, "Single source of truth (SSOT) for service oriented architecture (SOA)," in *Service-Oriented Computing* (Lecture Notes in Computer Science). Berlin, Germany: Springer, 2014, pp. 575–589, doi: 10.1007/978-3-662-45391-9_50.

[40] J. Mäule, T. Kutzler, T. Leich, D. Schäfer, and C. Richter, "Unified namespace and asset administration shell: A winning combination for digital production," in *Proc. IEEE 29th Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, vol. 2293, Padova, Italy, Sep. 2024, pp. 1–7, doi: 10.1109/ETFA61755.2024.10710821.

[41] V. Duvvur, "Legacy systems in the age of innovation: Strategies for seamless modernization," in *Design of Single Chip Microcomputer Control System for Stepping Motor*. Coventry, U.K.: Scientific Research and Community Ltd, Apr. 2024, doi: 10.47363/jaicc/2024(3)e197.

[42] P. Garcia and W. Sritriratanarak, "We need a theoretical framework for the modernization of industrial legacy systems," *Frontiers Ind. Eng.*, vol. 1, Nov. 2023, Art. no. 1266651, doi: 10.3389/fieng.2023.1266651.

[43] A. H. Adepoju, A. Eweje, A. Collins, and B. Austin-Gabriel, "Framework for migrating legacy systems to next-generation data architectures while ensuring seamless integration and scalability," *Int. J. Multidisciplinary Res. Growth Eval.*, vol. 5, no. 6, pp. 1462–1474, Jan. 2024, doi: 10.54660/.ijmrge.2024.5.6.1462-1474.

[44] V. L. Nogueira, F. S. Felizardo, A. M. M. M. Amaral, W. K. G. Assuncao, and T. E. Colanzi, "Insights on microservice architecture through the eyes of industry practitioners," 2024, *arXiv:2408.10434*.

[45] J. Kazanavicius and D. Mažeika, "An approach to migrate from legacy monolithic application into microservice architecture," in *Proc. IEEE Open Conf. Electr., Electron. Inf. Sci.*, Apr. 2023, pp. 1–6, doi: 10.1109/ESTREAM59056.2023.10135021.

[46] Y. Romani, O. Tibermacine, and C. Tibermacine, "Towards migrating legacy software systems to microservice-based architectures: A data-centric process for microservice identification," in *Proc. Int. Conf. Softw. Archit. Companion*, Mar. 2022, pp. 15–19, doi: 10.1109/ICSA-C54293.2022.00010.

[47] J. Christian, A. Kurniawan, and M. S. Anggreainy, "Analyzing microservices and monolithic systems: Key factors in architecture, development, and operations," in *Proc. 6th Int. Conf. Comput. Inform. Eng.*, 2023, pp. 64–69, doi: 10.1109/IC2IE60547.2023.10331155.

[48] C. Ma and B. Molnár, "A legacy ERP system integration framework based on ontology learning," in *Proc. 21st Int. Conf. Enterprise Inf. Syst.*, Jan. 2019, pp. 231–237, doi: 10.5220/0007740602310237.

[49] T. Kähkönen, K. Smolander, and A. Maglyas, "Lack of integration governance in ERP development: A case study on causes and effects," *Enterprise Inf. Syst.*, vol. 11, no. 8, pp. 1173–1206, Sep. 2017, doi: 10.1080/17517575.2016.1179347.

[50] P. Dhanekulla, "The role of middleware in integrating legacy systems with modern policy administration," *Int. J. Sci. Res. Comput. Sci., Eng. Inf. Technol.*, vol. 10, no. 6, pp. 397–406, Nov. 2024.

[51] M. Buttu, G. Carboni, A. Fara, M. Fiorentini, M. Landoni, C. Migoni, L. Monti, A. Orlati, S. Poppi, S. Righini, and F. R. Vitello, "A middleware to confine obsolescence," *Proc. SPIE*, vol. 12189, pp. 42–47, Jan. 2022, doi: 10.1117/12.2629971.

[52] M. Srinivas, G. Ramakrishna, K. R. Rao, and E. S. Babu, "Analysis of legacy system in software application development: A comparative survey," *Int. J. Electr. Comput. Eng. (IJECE)*, vol. 6, no. 1, pp. 292–297, Feb. 2016, doi: 10.11591/ijece.v6i1.8367.

[53] J. Opara-Martins, R. Sahandi, and F. Tian, "Critical analysis of vendor lock-in and its impact on cloud computing migration: A business perspective," *J. Cloud Comput.*, vol. 5, no. 1, pp. 1–18, Dec. 2016, doi: 10.1186/s13677-016-0054-z.

[54] I. V. Nitulescu and A. Korodi, "Supervisory control and data acquisition approach in node-RED: Application and discussions," *IoT*, vol. 1, no. 1, pp. 76–91, 2020. [Online]. Available: https://doi.org/10.3390/iot1010005

[55] M. Resman, M. Pipan, M. Simic, and N. Herakovic, "A new architecture model for smart manufacturing: A performance analysis and comparison with the RAMI 4.0 reference model," *Adv. Prod. Eng. Manage.*, vol. 14, no. 2, pp. 153–165, Jun. 2019, doi: 10.14743/apem2019.2.318.

[56] E. Y. Nakagawa, P. O. Antonino, F. Schnicke, R. Capilla, T. Kuhn, and P. Liggesmeyer, "Industry 4.0 reference architectures: State of the art and future trends," *Comput. Ind. Eng.*, vol. 156, Jun. 2021, Art. no. 107241, doi: 10.1016/j.cie.2021.107241.

[57] C. Koulamas and A. Kalogeras, "Cyber-physical systems and digital twins in the industrial Internet of Things [Cyber-physical systems]," *Computer*, vol. 51, no. 11, pp. 95–98, Nov. 2018, doi: 10.1109/MC.2018.2876181.

[58] F. Gosewehr, J. Wermann, and A. W. Colombo, "Assessment of industrial middleware technologies for the PERFoRM project," in *Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2016, pp. 5699–5704.

[59] L. M. Gorißen, J.-N. Schneider, M. A. A. Behery, P. Brauner, M. Lennartz, E. D. Kötter, T. Kaster, O. Petrovic, C. R. Hinke, T. Gries, G. Lakemeyer, M. Ziefle, C. Brecher, and C. L. Häfner, "Demonstrating data-to-knowledge pipelines for connecting production sites in the world wide lab," *ArXiv*, vol. abs/2412.12231, 2024. [Online]. Available: https://doi.org/10.48550/arXiv.2412.12231

[60] M. Yli-Ojanperä, S. Sierla, N. Papakonstantinou, and V. Vyatkin, "Adapting an agile manufacturing concept to the reference architecture model industry 4.0: A survey and case study," *J. Ind. Inf. Integr.*, vol. 15, pp. 147–160, Sep. 2019, doi: 10.1016/j.jii.2018.12.002.

[61] J. Kaiser, G. Hawkridge, G. Yilmaz, and D. McFarlane, "A low-cost integration approach for distributed manufacturing information systems," in *Proc. IEEE 5th Adv. Inf. Manage., Communicates, Electron. Autom. Control Conf. (IMCEC)*, Jun. 2022, pp. 1–14.

IOANA-VICTORIA NITULESCU received the B.S. degree in informatics and the M.S. degree in cloud computing and the Internet of Things from the Polytechnic University of Timisoara, Romania, in 2020 and 2022, respectively. Since 2019, she has been active in the industrial domain, with extensive experience as an Integration and Software Architect and an Associate Researcher. Her current research interests include Industry 5.0, OT-IT convergence, digital transformation applied to multiple sectors for efficiency and automation, and large-scale real-time interoperability.

ADRIAN KORODI (Member, IEEE) received the B.S., M.S., and Ph.D. degrees from Universitatea Politehnica Timişoara, in 2003, 2005, and 2008, respectively. He is currently an Associate Professor with the Department of Automation and Applied Informatics. He was the Director of various research grants and contracts, many of them involving the industry (e.g., water and wastewater, automotive, and BMS). Throughout the years, he was an Automation/SCADA Expert working mostly in the water industry, and completed more than 100 contracts of work. His research interests include the IIoT and Industry 4.0, with an emphasis on protocols, interoperation, and efficiency-increasing solutions in industry, security issues in automation, and SCADA systems.

DANIEL-IOAN CURIAC (Senior Member, IEEE) received the Ph.D. degree in automatic systems from the Politehnica University of Timisoara, Romania, in 1996. Since 2001, he has been a Full Professor at the Department of Automation and Applied Informatics, Politehnica University of Timisoara. He has published more than 140 papers in influential journals and conferences. His current research interests include cyber-physical systems, robotic systems, real-time adaptive systems, and information security.