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Towards Safety and Accuracy of Hydrogen Refuelling Stations through Digital Twins

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***Abstract* – This paper presents digital quality infrastructure methods for hydrogen refueling stations using the Asset Administration Shell as a standardized digital twin. Implemented at BAM's test platform, it integrates real-time sensor data, calibration certificates, and compliance documents to support traceable, interoperable asset management. In combination with AI and semantic tools, the system will enable predictive maintenance, remote audits, and improved safety. This approach reduces downtime, enhances transparency, and offers a scalable model demonstrating the potential of digital twins in advancing metrological traceability and operational efficiency in hydrogen technologies.**

I. INTRODUCTION

The quality infrastructure (QI) ensures the safety, reliability, and interoperability of products and services. Traditionally reliant on paper-based, oftentimes manual processes, QI is now being transformed by digital technologies. The German initiative QI-Digital brings together key stakeholders to develop integrated digital tools and ecosystems that modernize QI for today's production systems and global value chains [1]. Concrete use cases have been set up with dedicated R&D and test platforms established at the Federal Institute for Materials Research and Testing – Bundesanstalt für Materialforschung und -prüfung (BAM), one of the key players.

The use cases are centered around quality assurance in modern production and for technical facilities, whereas the latter is represented by a state-of-the-art hydrogen refueling station (HRS). As hydrogen applications and technologies scale up in response to the energy transition, the demand for solutions that ensure a safe and efficient operation is growing.

This paper presents approaches taken in our HRS reality lab to develop, test and demonstrate such digital QI solutions – applicable also for other types of technical facility and settings beyond hydrogen infrastructure. First, we introduce a vision for a digital QI in HRS and elaborate the role of digital twins. We then report on the implementation of digital QI in our HRS test platform building on the Asset Administration Shell (AAS). An outlook to potential extensions of the work concludes our paper.

II. QUALITY INFRASTRUCTURE FOR HRS: STATE OF THE ART AND VISION

Hydrogen refueling stations (HRS) are critical for the hydrogen mobility transition but pose significant safety and operational challenges due to risks like overpressure, leakage, and explosion. Moreover, an examination of the database of hydrogen-related incidents and accidents [2] emphasises the imperative for precise component specifications. Efficient access to information and tools is essential. Therefore, digital twins should integrate information on standards and relevant results from the quality infrastructure, including evaluation certificates.

HRS are subject to stringent safety, measurement accuracy and environmental compatibility requirements. International standards (e.g., SAE J2601, ISO 19880-1:2020) define strict operational limits, necessitating advanced monitoring and control systems. Independent testing organizations must verify that high-pressure and nozzle coupling systems, explosion-prone zones and calibrated, traceable dispensing measurements all meet technical and legal standards. Currently, these verifications are typically conducted through separate testing and certification processes, which often rely on extensive paper- or PDF-based documentation. Any modification, such as replacing a compressor, triggers a new time-consuming manual documentation process, which delays commissioning, increases costs, and reduces transparency for operators, authorities, and service partners. In addition, regular inspections of pressure vessels, hazardous area (Ex zone) assessments, and calibration of measurement and safety sensor systems are mandatory.

A digital QI that makes use of enhanced tools and processes as well as latest, standardized technologies can offer an efficient solution to these challenges. QI tools like machine-readable SMART standards, digital calibration and conformity certificates (DCC, D-CoC), test reports (DTR) and accordant digital trust system, process control system (PCS) data can be directly integrated into the AAS data system. All quality-, process-, and safety-relevant data – from temperature sensors to fill level monitoring – is collected in real time in a digital container. This data is structured as an AAS and is fully linked to the PCS. This eliminates discontinuities between different media, accelerates workflows and ensures interoperability, preventing costly issues from arising during operation.

Operators benefit from reduced downtime and real-time access to compliance status. Testing organizations can perform remote audits using machine-readable, real-time data in digital SI format, while service original equipment manufacturers (OEMs) can use verified original data for predictive maintenance algorithms. A digital QI thus can transform the complex safety and measurement chain of a HRS into a transparent, real-time data flow — an approach that can be applied to any technical system with high compliance requirements.

Digital twins (DT) offer a powerful means to model these systems virtually, enabling timely monitoring, predictive maintenance, and AI-driven optimization. The next section outlines the state of art of DT for HRS.

III. DIGITAL TWINS FOR HRS

A digital twin is defined as a digital representation of a physical product, system or service that is linked to it throughout its entire life cycle. The objective is to facilitate analysis, optimization, control and simulation of technical systems, with a particular emphasis on real-time applications. [3]

A. *State of the Art*

Digital twins facilitate data management and access, including in complex technical facilities such as hydrogen refueling stations.

Safety and Monitoring. Digital Twins are increasingly recognized as key enablers for improving HRS safety, efficiency, and reliability. They integrate real-time sensor data, IIoT (Industrial Internet of Things), and AI to simulate and monitor system behavior. Several studies propose DT frameworks that incorporate statistical process control, real gas modeling, and MATLAB simulations to monitor parameters such as hydrogen flow and temperature [4]. A mobile DT-based leak detection system combines IoT sensors with geospatial mapping (e.g., Google Maps) and time-series databases to enable location-specific, real-time safety monitoring [5].

AI-Enhanced Simulation and Risk Prediction. Advanced DT models leverage machine learning for predictive analytics. One approach integrates real-time sensor data into a 3D simulation using convolutional neural networks (CNNs) and Unity 3D to visualize and predict hazardous conditions, supporting rapid decision-making [6]. Another review highlights the role of AI techniques – such as deep learning, reinforcement learning, and federated learning –across the hydrogen value chain, emphasizing lifecycle coverage, model interpretability, and regulatory compliance [7].

Architectures and Technical Challenges. A comprehensive review outlines digital twin architectures comprising data, integration, and application layers, with features like real-time monitoring, predictive maintenance, and 3D visualization [8]. Key challenges include data scarcity, computational demands, and algorithm robustness. Standardization of data formats, cybersecurity, and scalability across diverse HRS configurations remain open research areas. Current efforts focus on interoperable platforms, federated data spaces, and AI-driven analytics to address these gaps.

B. *Challenges*

The effectiveness of DTs hinges on overcoming several key challenges, particularly regarding data quality and QI:

Data Integration and Interoperability. HRS components often originate from diverse manufacturers, requiring standardized data models and semantic to ensure consistent, high-quality data exchange across systems.

Sensor Reliability and Data Quality. DTs depend on accurate, real-time sensor data under extreme conditions (e.g., high pressure). Ensuring sensor calibration, redundancy, and fault detection is critical to maintaining model integrity and avoiding unsafe decisions.

Quantification of Uncertainties. Interoperability and traceability are important goals. Calibration of sensors is a very important step towards these goals; however, the quantification of uncertainties identified along the measurement chains is no less important to achieve these goals. Thus, in the future we should also quantify these uncertainties. This especially applies if an AI approach is implemented, as models should be trained and validated considering these uncertainties.

Model Validation and Responsiveness. High-fidelity simulations of thermodynamic and fluid processes must be continuously validated against real-world data. Balancing model accuracy with real-time performance remains a persistent challenge.

Quality Infrastructure and Metrological Traceability. A fundamental yet frequently disregarded challenge pertains to the incorporation of quality infrastructure – comprising metrology, standardization, certification, and conformity assessment – into digital twin ecosystems. A robust digital QI is essential for ensuring the traceability of key measurements (pressure, temperature, flow) to standards. DTs should support sensor calibration, model validation, and compliance with technical norms to ensure data reliability and regulatory acceptance – especially vital in safety-critical applications like hydrogen fueling.

Cybersecurity and Governance. As DTs operate within connected ecosystems, secure data handling, access control, and regulatory compliance are non-negotiable. Proprietary Solutions. Accessing data across stakeholders such as manufacturers, operators, or calibration labs requires familiarity with proprietary systems and their semantics, due to the lack of standardized, industry-neutral interfaces.

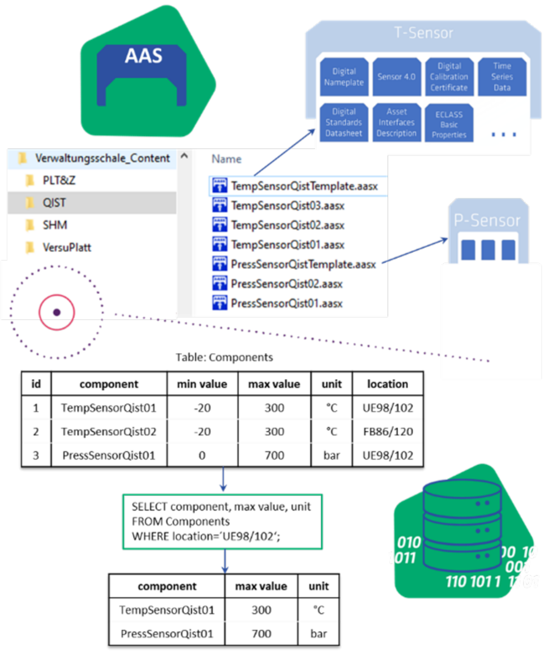

Fig. 1. Differences between Asset Administration Shell (top) and relational databases (bottom)

Many digital twins remain proprietary, tailored to specific tools (e.g., MATLAB, ANSYS) or platforms (e.g., Azure, AWS), often lacking semantic interoperability. The Asset Administration Shell employs defined interfaces, data models and semantics to facilitate interoperability.

C. *Asset Administration Shell (AAS)*

The AAS represents a standardized subset within the broader digital twin landscape, particularly suited for regulated, multi-stakeholder contexts requiring traceability and data sovereignty. As the standardized digital twin of a physical or logical asset, it enables semantic interoperability and consistent lifecycle management. It provides a structured, machine-readable interface for data exchange, control, and integration within Industry 4.0 environments such as HRS.

The AAS is structured modularly, comprising submodels that represent specific asset aspects—such as identification, documentation, or condition monitoring—using standardized semantics [9]. This allows flexible adaptation to various use cases while ensuring interoperability. For example, a temperature sensor's AAS may include submodels for identification, calibration, live data, diagnostics, and compliance (e.g., ISO/IEC 17025). To ensure compatibility, submodels should follow *Industrial Digital Twin Association (IDTA)* specifications, developed with industry and research partners, and aligned with international standards.

Relational databases are powerful for managing structured data, offering centralized querying and aggregation. However, they often lack standardized semantics and interoperable interfaces, making cross-organizational data exchange difficult and reliant on project-specific knowledge. The AAS takes a different approach by using a hierarchical, file-based XML structure to represent each asset (cf. Fig. 1). While it lacks centralized querying, its strength lies in providing a standardized, decentralized, and self-contained digital interface for asset data. Rather than replacing databases, the AAS complements them by adding a semantic layer that supports interoperable data exchange, system integration, and digital lifecycle management.

With this, the AAS represents a valuable tool to enable the integration of digital QI processes and tools allowing for advanced quality assurance of HRS. The next section presents insights from the ongoing implementation in our HRS test platform.

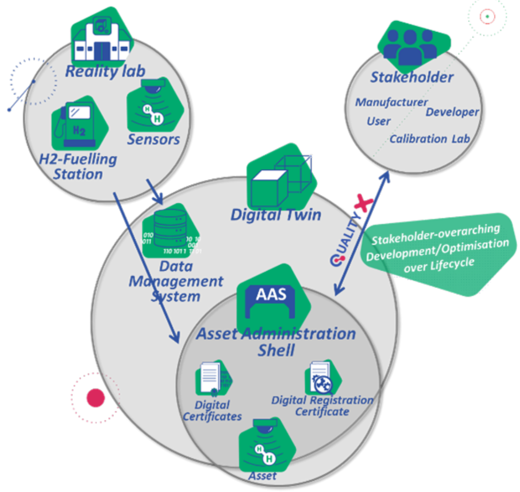

Fig. 2. Digital Twin of BAM's Reality Lab with AAS

IV. IMPLEMENTATION IN THE HRS TEST PLATFORM

The HRS at BAM functions as a testbed, thus facilitating collaboration with industry and research partners [10]. This enables the implementation of new or modified digital QI methods within a real-life technical facility. The initial notions of data retrieval, management and sharing are presented, in addition to the interplay between multiple processes.

A. *Test Platform*

Our QI-Digital reality lab comprises a complete state-of-the-art hydrogen refueling station (HRS) augmented with technologies such as sensors and monitoring systems (see Fig. 2). The test platform is supplied with green hydrogen and incorporates advanced process control technologies,

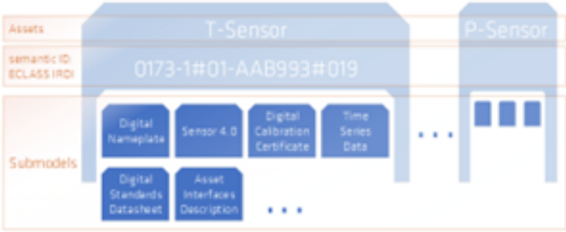

Fig. 3. Structure of the Asset Administration Shell

contributing to the development of robust digital standards and infrastructures that support the safe, scalable deployment of hydrogen technologies. Within this setup, various types of data are generated, including process data (time series from sensors), sensor metadata, and associated documentation and certificates. These data are stored in a proprietary data management system. To effectively manage, analyze, and utilize this heterogeneous, dynamic data, the implementation of a digital twin station – a virtual representation of the physical system – becomes essential and serves as a foundational tool for advancing quality assurance in digitally transformed technical systems.

B. *Integrating the Asset Administration Shell*

Our concept involves mapping selected assets and relevant documents in our proprietary data management system using AAS (cf. Fig. 2). For instance, this could be a temperature sensor used to monitor the refueling process, including the associated digital calibration certificate (DCC) [11]. We primarily use IDTA-published submodels for this purpose. This enables different stakeholders to access these standardized AAS without requiring knowledge of the proprietary data management systems of other organizations. The focusses here are on metadata, digital certificates, and process data.

C. *Data Modeling through submodels*

Submodel templates like Technical Data, Digital Nameplate, and Time Series Data were selected for the HRS test bed. The DCC submodel, central to *UseCaseH2*, includes calibration certificates and supports metrological standards, even though not yet officially published [12].

D. *Semantics through ECLASS dictionary*

ECLASS is a globally recognized semantic dictionary that enables machine-readable, interoperable asset descriptions [13]. Recommended by *Plattform Industrie 4.0* for AAS implementations, it ensures unambiguous, standardized semantics through unique identifiers (IRDIs), as shown in Fig. 3. The AAS natively integrates with the ECLASS catalogue, allowing direct import of assets and submodels using standardized classifications. This supports reusable, harmonized submodels across domains, enhancing semantic interoperability and digital quality infrastructure. It also facilitates traceable, verifiable, and auditable asset descriptions for compliance, certification, and lifecycle documentation. It is evident that the prototype under consideration employs the ECLASS vocabulary to facilitate interoperability among multiple stakeholders regarding the description of QI-related assets.

Fig. 4. AAS of a temperature sensor in AASX Package Explorer with Calibration Certificate

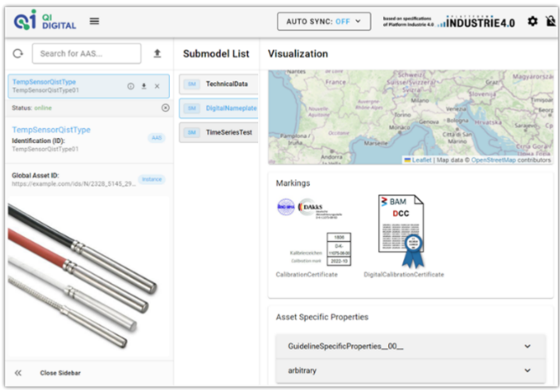

Fig. 5. BaSyx Web UI for AAS

E. *Testbed at BAM*

Various procedures exist for creating AAS, which should be used in the different implementation phases. Initially, the AAS are created manually via the Graphical User Interface (GUI) of the AASX Package Explorer software (see Fig. 2). To interact with and visualize the created AAS, an instance of the web GUI of the Eclipse BaSyx project has been implemented (cf. Fig. 5).

AAS templates with the relevant submodels are created for asset types (e.g. temperature sensors) and filled with metadata valid for sensors types (e.g. manufacturer). Then, an AAS instance is cloned from an AAS template and its submodels are manually filled with instance-specific metadata (e.g. the serial number) via the GUI. This creates ad-

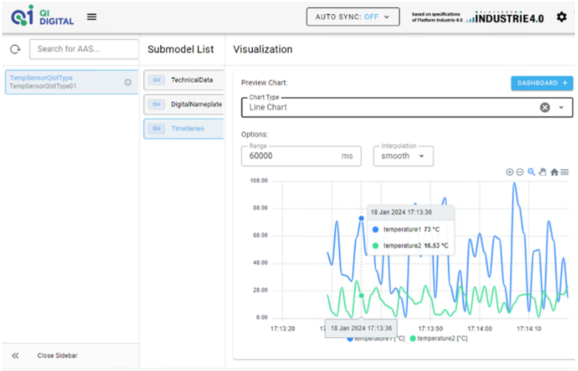

Fig. 6. Submodel Time Series Data

ministration shells for selected assets that contain all the relevant metadata available.

All the asset's existing metadata is stored in the Digital Nameplate submodel. This includes digital QI documents (e.g. a temperature sensor's calibration certificate). As soon as the DCC submodel becomes available, these documents will be stored there instead. Measurement data (e.g. H2 temperature during the fueling process) is stored in the Time Series Data submodel in the form of CSV files. These can be visualized interactively (see Fig. 6). Technically, an automated import of measurement data could also be implemented.

F. Use Case upon Quantitative Risk Assessment

The need of a standardized infrastructure and its support for process and safety optimization is demonstrated in a use case upon Quantitative Risk Assessment (QRA) at BAM [14]. Key of the assessment is building a database of different hydrogen refueling stations. The more data, the better the probabilistic statements can be supported. Therefore, the data must be accessible from the sensor field level and interpretable in terms of their semantics. Specially if stakeholders beyond other ecosystems are involved. In this regard a framework is deployed for transforming PCS data into the QRA database. The framework retrieves data from the Process Control System (PCS) via an API (application programming interface) embedded or described within the station's asset administration shell, which is accessible exclusively through a secure Virtual Private Network (VPN). The collected data include all executed control commands, process variables, automatically generated fault logs from system components, and triggered alarms. This data acquisition occurs at fixed intervals, with the system processing the data between each retrieval cycle. Further documentation on all sensors and actuators can be accessed via the AAS. On that account the framework is capable to work with other environments that support AAS and enhance the automation on processing data.

V. DIGITAL TWINS ENVISION QI APPLICATIONS

The complexity and safety-critical nature of hydrogen infrastructures demand innovative solutions for monitoring, control, and optimization. The integration of digital twins and artificial intelligence (AI) offers a transformative approach.

Digital twins – dynamic, virtual models synchronized with real-time plant data – combine current system states with historical, physical, and semantic data, creating a rich environment for training and deployment. Digital twins are essential for safety-critical systems, providing structured, interpretable data streams. Without them, application deployment would involve significant uncertainty and risk. Key scenarios include:

Condition Monitoring & Predictive Maintenance. DT replicate physical assets of a HRS – including storage tanks, compressors, valves, and sensors – in a virtual environment. AI techniques like anomaly detection with autoencoders or time-series analysis with long short-term memory (LSTM) networks enable fault detection at early stages and demand-driven maintenance, improving availability and reducing costs.

Energy & Resource Efficiency. Algorithms, supported by historical and real-time data, can optimize energy flows. Reinforcement learning helps reduce compressor energy use and adapt cooling strategies, lowering load peaks and emissions.

Real-Time Safety Management. AI can detect critical conditions through pattern recognition (e.g., pressure spikes) and triggers emergency protocols. DT also support forensic analysis by reconstructing past states.

Simulation & Training. Virtual environments allow staff to train in realistic scenarios. AI can personalize learning paths and simulate incidents to improve readiness.

Integration with Energy Systems. Coupling digital twins with smart grids and mobility platforms enables dynamic control of HRS within broader energy networks. Forecasting models support demand-driven energy supply and pricing – key for fleet operators and sector coupling.

VI. CONCLUSION AND OUTLOOK

As a key principle of the AAS is to support assets throughout their lifecycle, collaboration with suppliers or manufacturers is recommended. Given the high value of data and the AAS's interoperability, this approach offers significant potential for multi-stakeholder access. A team is developing predictive maintenance use case for high-pressure gas tanks, such as those at hydrogen refuelling stations, using AI-based acoustic and ultrasound technologies. Achieving this requires collaboration with software and hardware providers to integrate DCC of pressure sensors into industrial control systems and deliver traceable, metrology-validated DT-based subsystems to stakeholders.

VII. Acknowledgements

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