BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 72 (76), Numărul 3, 2026
Secţia
CONSTRUCŢII DE MAŞINI
DOI: 10.2478/bipcm-2026-0027

CONCEPTUAL DIGITAL TWIN ARCHITECTURE FOR INTEGRITY OF HDPE BUTT FUSION WELDS

BY

DANIEL- LUCIAN VATAVU and ADRIANA MUNTEANU*

“Gheorghe Asachi” Technical University of Iaşi,
Faculty of Machine Manufacturing and Industrial Management

Received: June 30, 2026
Accepted for publication: July 13, 2026

Abstract. High-density polyethylene (HDPE) pipelines are extensively used in water and gas distribution systems due to their excellent corrosion resistance, durability, flexibility, and low maintenance requirements. The long-term reliability of these systems depends primarily on the quality of butt fusion welded joints, which represent the most critical locations in terms of structural integrity. In current practice, the quality assessment of HDPE welded joints is based on monitoring welding process parameters, visual inspection, mechanical testing, and non-destructive testing (NDT) methods. Although each of these approaches provides valuable information regarding weld quality, the resulting data are generated at different stages of the weld life cycle and are typically stored and studied independently. The present paper proposes a conceptual Digital Twin architecture for the integrity assessment of HDPE butt fusion welds, based on the correlation of welding process parameters, characteristic defects, and inspection results within a Knowledge Graph model to support decision-making.

Keywords: butt fusion weld, digital twin, high-density polyethylene.

*Corresponding author; *e-mail*: adriana.munteanu@academic.tuiasi.ro
© 2026 Daniel-Lucian Vatavu and Adriana Munteanu
This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

1. Introduction

In current practice, the quality assessment of HDPE welded joints is based on monitoring welding process parameters, visual inspection, mechanical testing, and non-destructive testing (NDT) methods. Although each of these approaches provides valuable information regarding weld quality, the resulting data are generated at different stages of the weld life cycle and are typically stored and investigated independently.

This limits the ability to make a correct assessment of the structural integrity of the weld and reduces the ability to detect defects early and estimate the remaining service life of the joint. A conceptual Digital Twin (Dihan *et al*., 2024) can overcome these limitations by integrating all available data sources into a global virtual representation of the weld, enabling dynamic condition monitoring, defect prediction, and informed inspection and maintenance decisions.

High-density polyethylene (HDPE) has become an indispensable material in numerous sectors, ranging from municipal water and gas distribution networks to complex industrial applications, including nuclear power plants, petrochemical facilities, and desalination plants. Since the production of the first polyethylene pipes in 1945, the material has evolved through advanced generations such as PE80, PE100, and, more recently, PE100-RC (Alhatti *et al*., 2025), which provides superior performance under high-pressure operating conditions. The growing demand for high-capacity infrastructure has led to the manufacture of pipes with diameters of up to 3500 mm, introducing unique technical challenges in the joining process. Therefore, HDPE pipelines have attracted increasing research interest due to their lower environmental impact compared with metallic pipelines, requiring less energy during production while offering excellent corrosion resistance and extended service life.

Research on HDPE butt fusion joints (BFJs) is of paramount importance because welded joints represent the weakest and most vulnerable components of pipeline systems subjected to operational loading. Current research is primarily motivated by several key challenges.

First, ensuring long-term reliability is essential, as HDPE pipeline systems are designed for service lives of up to 100 years. Current studies focus on understanding the interdiffusion mechanisms of polymer chains during the welding process to ensure that the mechanical strength of the welded joint equals or exceeds that of the parent material (Pathak and Pradhan, 2019).

Second, significant efforts are directed toward optimizing welding parameters by establishing the optimal balance between heating temperature, interface pressure, and heating and cooling times. Recent studies have demonstrated that operating at temperatures above conventional recommendations (e.g., 250°C), combined with reduced interface pressure, can improve weld toughness without inducing thermal degradation of the polymer.

Third, the reliable detection of critical welding defects remains a major research challenge. Defects such as cold welds, insufficient molecular diffusion, and fine contaminations may remain undetected using conventional visual inspection or ultrasonic testing. As a result, novel inspection techniques, including the Hydro-Axial Tension (HAT) method, have been developed to evaluate the entire weld cross-section and improve defect detection capability.

In conclusion, research is particularly important for safety-critical applications such as nuclear power plants, where pipeline integrity is directly associated with operational safety. Recent investigations into slow crack growth have shown that butt fusion welds may be up to thirty times more susceptible to crack propagation than the parent pipe material, emphasizing the need for advanced monitoring, predictive assessment, and intelligent integrity management throughout the pipeline life cycle (Ramadan and Tanase, 2021).

The increasing adoption of Industry 4.0 technologies creates new opportunities for integrating heterogeneous data into intelligent monitoring systems. This paper proposes a conceptual Digital Twin framework for HDPE butt fusion welds that combines welding process parameters, NDT inspection results, and acceptance criteria defined by relevant technical standards into a unified virtual representation of the welded joint. By integrating welding, inspection, and integrity data into a single digital model, the assumed design supports continuous condition assessment, defect prediction, and informed inspection and maintenance decisions, improving both weld quality assessment and pipeline integrity management.

A Knowledge Graph, in this particular case, is the ideal tool for this process because it acts as a central brain that understands how all the factors involved influence each other (Yu *et al*., 2025; Sahlab *et al*., 2021; Listl *et al*., 2024). Thus:

– Sees the big picture, not just fragments: Normally, data on pressure, material temperature or visual inspection results are stored separately. The Knowledge Graph creates logical connections between welding parameters, material properties and environmental conditions.

– Understands “why”, not just “what”: Unlike a classic database, this digital model can make reasoning. For example, it does not just see a drop in pressure, but can correlate that drop with a specific mechanism of defect formation, such as cold fusion.

– A map of knowledge throughout its life: The model allows for full traceability. One can follow the course of a weld from the execution phase to decades of operation, reusing the accumulated knowledge to predict when problems might arise.

– Helps experts make better decisions: By automatically correlating inspection evidence with technical standards, the system eliminates human subjectivity. It provides clear recommendations – whether the weld should be accepted, repaired, or replaced – transforming raw data into concrete actions.

This method has already been successfully tested in smart manufacturing and gas network management, demonstrating that when data "talks" to each other via a Knowledge Graph, pipeline maintenance becomes much safer and more efficient.

2. Digital Twin Architecture

A Digital Twin (DT) is a dynamic virtual representation of a physical object, process, or system that remains continuously connected to its real-world counterpart through bidirectional data exchange (Yu *et al*., 2025). First introduced by NASA during the Apollo program, the Digital Twin concept has evolved into a key enabling technology for real-time monitoring, predictive analysis, and lifecycle optimization. Its effectiveness relies on the continuous flow of data, which serves as the foundation for maintaining synchronization between the physical and virtual environments and to supporting intelligent decision-making (Shaiju, 2024).

The process by which real-world data is transformed into digital models (Digital Twins) is a complex and dynamic one, involving several essential stages that allow the creation of an accurate virtual representation. The main steps are emphasized in Fig. 1.

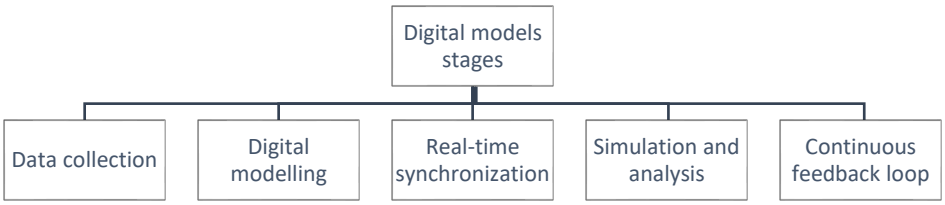


Fig. 1 – Digital Twins levels.

In case of data collection, it all starts with gathering information through sensors, IoT devices and historical records. These sensors monitor parameters such as temperature, humidity, structural integrity and energy consumption of physical objects or systems in real time. After, the collected data is used to create a 3D digital model. Unlike a simple mock-up, this is a dynamic simulation that automatically changes as new data is entered. Modern software platforms ensure the realism and accuracy of these models (Listl *et al*., 2024; Sahlab *et al*., 2022).

The Digital Twin architecture ensures in step three, real-time synchronization, that any change that occurs in the real world is instantly reflected in the digital model. In next stage, the digital model runs various simulations to see how the building or system performs under different conditions (stress tests, environmental impact, energy consumption). This helps identify risks and optimize processes before their physical implementation.

The final step is to establish a continuous flow of data from the real object to the digital twin. This loop ensures that the model remains up-to-date and accurate, providing valuable information for maintenance and operational efficiency (Dihan *et al*., 2024; Yu *et al*., 2025).

Through this workflow, raw data becomes a powerful tool that allows architects and project managers to visualize and optimize every stage of a structure's life cycle, Fig. 2.

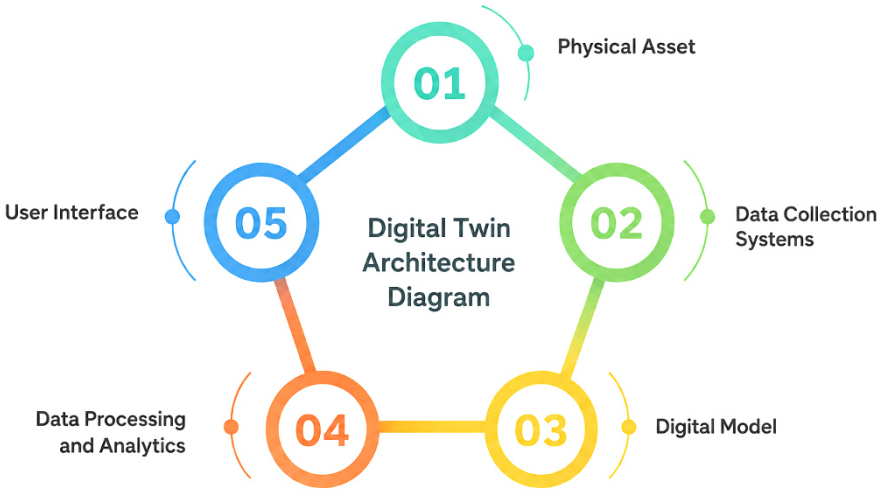


Fig. 2 – Digital Twin diagram, modified after (Shaiju, 2024).

3. Proposed Digital Twin Architecture

The Digital Twin architecture is structured as a multilayer framework composed of six interconnected functional layers, designed to ensure a continuous exchange of information between the physical welded joint and the virtual model. This hierarchical organization enables the transformation of raw process and inspection data into meaningful engineering knowledge, ultimately supporting informed decision-making throughout the lifecycle of HDPE pipeline systems.

At the foundation of the architecture is the Physical Weld Layer, which represents the real-world asset, namely the HDPE pipe and its butt fusion welded joint. This layer embodies the actual condition of the weld and serves as the primary source of information regarding manufacturing parameters, inspection outcomes, and operational performance. As the welded joint evolves during service, the physical layer continuously generates data reflecting its structural state and integrity.

The second level, referred to as the Data Acquisition Layer, is responsible

for registration and organizing information related to both the welding process and the subsequent condition of the joint. Typical inputs include heater plate temperature, fusion pressure, heating and cooling durations, pipe alignment, environmental conditions during welding, and the results obtained from non-destructive testing (NDT) techniques. By consolidating these heterogeneous data streams, this layer establishes the digital foundation upon which the virtual representation of the weld is constructed.

At the core of the proposed model are the Knowledge Graph and the Digital Model Layer, which function as the central intelligence of the Digital Twin. Unlike conventional databases that store information in isolated records, the knowledge graph establishes relationships between welding parameters, material characteristics, failure mechanisms, inspection findings, and weld integrity indicators. This interconnected representation allows for the capture of cause-and-effect relationships, enabling knowledge reuse and supporting advanced reasoning processes. As new inspection data becomes available, the digital model can be continuously updated, ensuring that the virtual representation remains synchronized with the physical model.

Based on this knowledge-based foundation, the Defect Prediction Level aims to identify and assess the probability of defects occurring within the welded joint. By integrating process parameters, inspection records over time, and known defect formation mechanisms, the Digital Twin can infer the potential development of characteristic imperfections such as lack of fusion, cold fusion, misalignment, contamination, and material inhomogeneity. This predictive capability assures the opportunity to detect quality issues at an early stage, reducing the reliance on costly or time-consuming destructive testing procedures.

The subsequent Integrity Assessment Layer translates defect-related information into engineering indicators that characterize the structural condition and reliability of the welded joint. These indicators may include an altogether Integrity Index, qualitative or quantitative risk classifications, and estimations of remaining service life. By combining manufacturing data, inspection results, and engineering knowledge, this layer provides a holistic evaluation of weld performance and supports the assessment of long-term structural integrity.

At the highest level of the framework resides the Decision Support Layer, where the outputs generated by the integrity assessment are converted into actionable engineering recommendations. Depending on the evaluated condition of the weld, the system may suggest acceptance of the joint, additional inspection activities, corrective repair actions, or complete replacement. So, the proposed Digital Twin extends beyond the role of a monitoring platform and evolves into a knowledge-driven decision-support environment capable of assisting inspectors, asset managers, and pipeline operators in optimizing maintenance strategies and ensuring safe long-term operation.

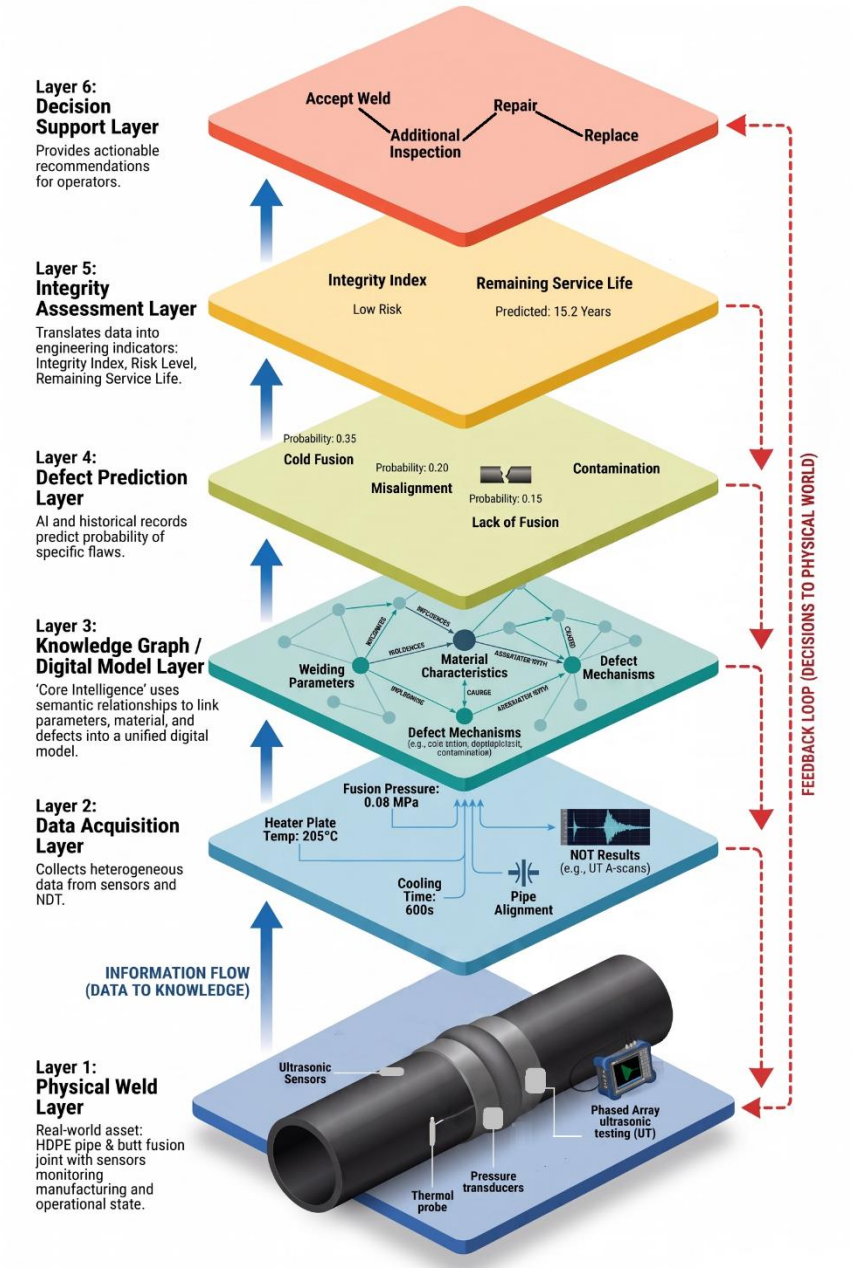


Fig. 3 – Digital Twin architecture as a multi-layered.

Generally, the proposed layered architecture establishes a coherent pathway from data acquisition to engineering decision-making.

By integrating process monitoring, knowledge representation, defect

prediction, and integrity evaluation within a single framework, the Digital Twin provides a conceptual foundation for intelligent inspection, predictive maintenance, and digital lifecycle management of HDPE butt fusion welded joints, Fig. 3.

If we considered bidirectional information flow, the architecture in the case of butt welding would be more concise, Fig. 4.

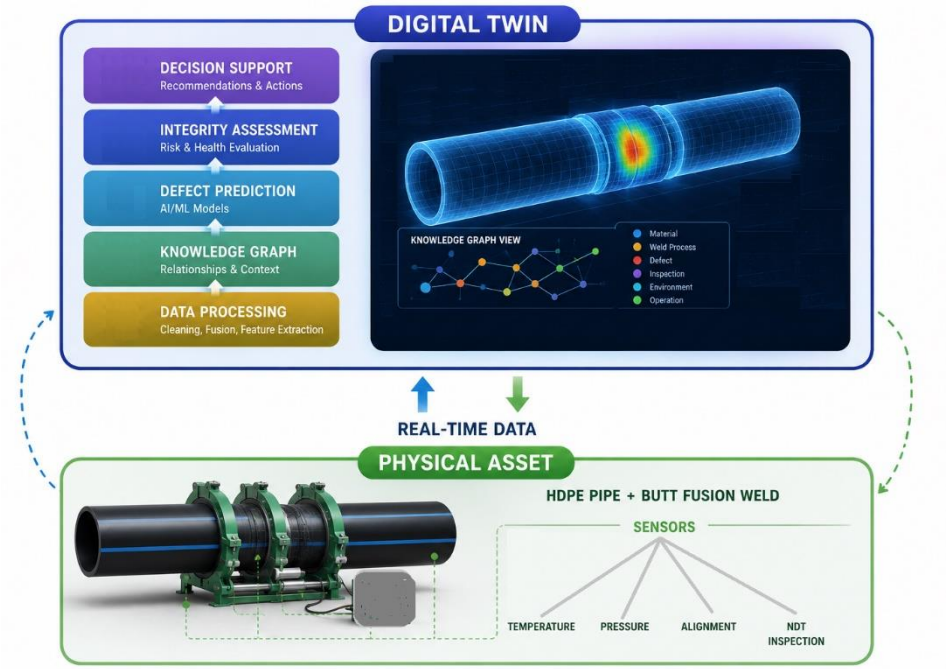


Fig. 4 – Butt weld digital twin architecture.

The Digital Twin is organized as a hierarchical workflow that transforms raw process data into engineering knowledge and decision support. The architecture begins with the Physical Weld, representing the real HDPE pipe and butt fusion joint that constitute the monitored asset throughout its service life.

The Data Acquisition layer continuously collects information generated during the welding process and subsequent inspections. This includes welding process parameters, environmental conditions, sensor measurements, and the results of non-destructive testing (NDT), thereby creating the digital representation of the physical asset.

For support the paper's Digital Twin architecture, a Knowledge Graph, as layer 3, is very suitable because it allows the integration of information from heterogeneous sources (welding machine, operators, NDT tests, mechanical

results, standards, etc.) and highlighting the relationships between them, as in Fig. 5.

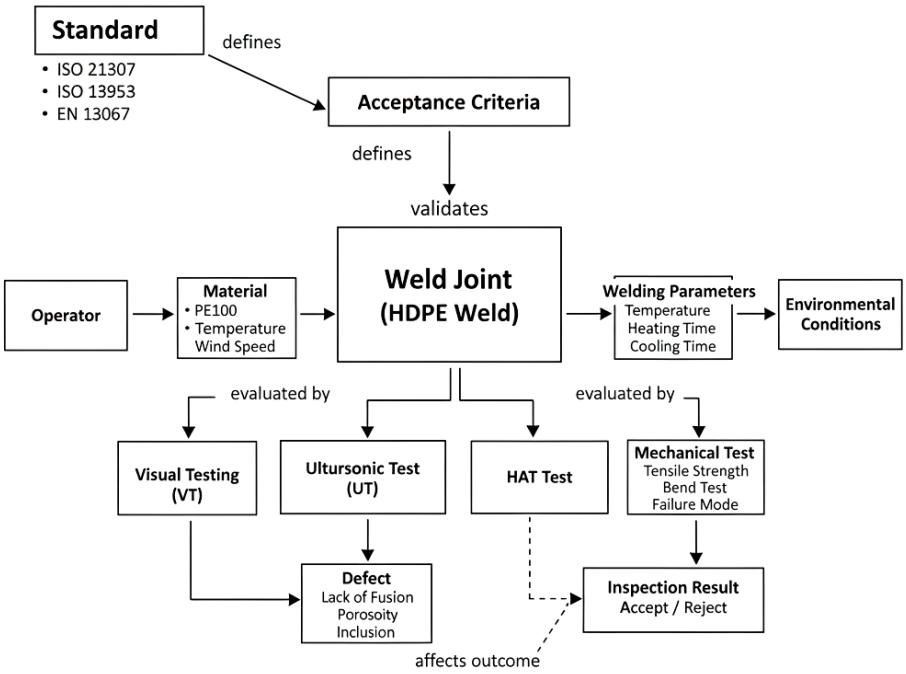


Fig. 5 – Conceptual model of the Knowledge Graph.

This Digital Twin architecture provides a connected structure for the digital assessment of HDPE butt fusion weld integrity by integrating information that is traditionally divided across different inspection and monitoring activities. By consolidating welding process parameters, non-destructive testing (NDT) results, defect characterization, mechanical performance indicators, and engineering standards into a single Knowledge Graph. This structure enables a comprehensive representation of the welded joint throughout its lifecycle. This integrated approach improves data consistency and traceability while facilitating a more holistic evaluation of weld quality.

In the context of Knowledge Graphs, as they are applied in the Digital Twin architecture described, examples of Subject-Predicate-Object relationships, as the fundamental unit of information storage and organization, are shown in the Fig. 6. These serve to establish logical connections between heterogeneous data, which allow for HDPE welds to track the course of a weld from the execution phase to decades of operation, reusing the accumulated knowledge.

<Standard> -> [defines] -> <Acceptance Criteria>

<Acceptance Criteria> -> [validates] -> <Weld Joint>

<Weld Joint> -> [has] -> <Welding Parameters>

<Weld Joint> -> [evaluated by] -> <Ultrasonic Test>

<Ultrasonic Test> -> [detects] -> <Defect>.

<Defect> -> [affects outcome] -> <Inspection Result>

Fig. 6 – Subject-Predicate-Object relationships of HDPE welds.

Based on these relationships results and another significant advantage of the architecture proposed in the paper, is the reduction of human-related variability during the inspection and assessment process. Conventional weld evaluation often depends on the experience and subjective judgment of inspectors, particularly when interpreting complex inspection results or correlating them with process conditions. By incorporating rule-based reasoning and semantic relationships, (for example: *<Defect> — affects outcome — <Inspection Result>*, the system provides objective and reproducible assessments) the Digital Twin provides consistent recommendations, thereby supporting inspectors with objective and reproducible assessments.

4. Conclusions

This paper presents a conceptual Digital Twin architecture for the integrity assessment of HDPE butt fusion welds. The model integrates welding process parameters, characteristic weld defects, non-destructive testing results, mechanical performance indicators, and engineering standards within a Knowledge Graph-based digital model. By establishing semantic relationships among these heterogeneous data sources, the architecture provides a coherent representation of the welded joint and supports integrity evaluation throughout its lifecycle.

The proposed architecture demonstrates how Digital Twin technologies can extend conventional inspection methodologies by transforming isolated measurements into actionable engineering knowledge. Through the integration of a Knowledge Graph and an AI/rule-based reasoning layer, the architecture enables defect prediction, integrity assessment, and engineering decision support, contributing to more reliable inspection and maintenance strategies for HDPE pipeline systems.

The combination of Digital Twins and Knowledge Graphs is an ongoing research activity, which demonstrates the relevance of this approach; however, experimental validation of this architecture is necessary. The key element of the system is a Knowledge Graph, which will allow the correlation of welding process variables with characteristic defects and non-destructive testing results to support decision-making.

Although this study is limited to the conceptual design of the Digital Twin, it provides a foundation for future intelligent systems supporting automated weld integrity assessment and predictive maintenance.

The six-level functional structure of the digital model will allow for continuous monitoring, defect prediction and joint lifetime estimation. Implementation of this model in future research aims to reduce human subjectivity in the inspection process and optimize maintenance strategies for HDPE weld.

Future work will address experimental validation, Knowledge Graph implementation, AI-driven analytics, and real-time integration between physical and digital assets for HDPE pipeline integrity management.

REFERENCES

Alhatti A.I., Deveci S., Barsoum I., Hosny A.I., *Avancements in butt fusion jointing of HDPE pipes: A comprehensive review of fusion conditions and joint integrity assessment techniques,* Polymer Testing *150* (2025).

Dihan S., Akash A.I, Tasneem Z., Das P., Das S.K, Islam R., Islam M., Badal F.R, Ali F., Md. Hafiz A, Abhi S.H, Sarker S.K., Hasan M., *Digital twin: Data exploration, architecture, implementation and future,* Heliyon *10* (2024).

Listl F.G., Dittler D., Hildebrand G., Stegmaier V., Jazdi N, Weyrich M., *Knowledge Graphs in the Digital Twin: A Systematic Literature Review About the Combination of Semantic Technologies and Simulation in Industrial Automation*. IEEE Access (2024).

Pathak S., Pradhan S.K., *Experimentation and optimization of HDPE pipe electro fusion and butt fusion welding processes*, Mater Today Proc (2019).

Ramadan I., Tanase M.*, Experimental study regarding the influence of welding parameters on the mechanical behavior of high-density polyethylene pipes*, Mater. Plast. *57* (2021).

Sahlab N., Braun D., Köhler C., Jazdi N., Weyrich M., *Extending the intelligent digital twin with a context modeling service: A decision support use case*, 55th CIRP Conference on Manufacturing Systems, Proc. CIRP, vol. 107, Jan. 2022, Vienna, Austria, 463-468.

Sahlab N., Kamm S., Müller T., Jazdi N., Weyrich M., *Knowledge graphs as enhancers of intelligent digital twins*, in Proc. 4th IEEE Int. Conf. Ind. Cyber-Phys. Syst. (ICPS), May 2021, Canada, 19-24.

Shaiju Th., *Digital Twin Architecture - Advantages and Disadvantages*, 2024, https://www.toobler.com/blog/digital-twin-architecture.

Yu Z., Zhou J., Wang Q., Zhou H., Song Y. Zong Ch.., *Construction of knowledge graph for gas polyethylene pipelines based on ALBERT-BiGRU-CRF*, Scientific Reports,*15*, 25002, (2025).

** *Polyethylene Pipe Butt Fusion Structure*, Process, and Terminology, PPI TN-51 2026 Edition.

ARHITECTURĂ CONCEPTUALĂ DIGITAL TWIN PENTRU EVALUAREA INTEGRITĂȚII SUDURILOR CAP LA CAP DIN HDPE

(Rezumat)

Conductele din polietilenă de înaltă densitate (HDPE) sunt utilizate pe scară largă în sistemele de distribuție a apei și gazelor datorită rezistenței lor excelente la coroziune, durabilității, flexibilității și cerințelor reduse de întreținere. Fiabilitatea pe termen lung a acestor sisteme depinde în primul rând de calitatea îmbinărilor sudate cap la cap, care reprezintă cele mai critice puncte din punct de vedere al integrității structurale. În practica actuală, evaluarea calității îmbinărilor sudate din HDPE se bazează pe monitorizarea parametrilor procesului de sudare, inspecția vizuală, testarea mecanică și metodele de testare nedistructivă (NDT). Deși fiecare dintre aceste abordări oferă informații valoroase privind calitatea sudurii, datele rezultate sunt generate în diferite etape ale ciclului de viață al sudurii și sunt de obicei stocate și analizate independent. Prezenta lucrare propune o arhitectură conceptuală Digital Twin pentru evaluarea integrității sudurilor HDPE prin fuziune cap la cap, bazată pe corelarea parametrilor procesului de sudare, a defectelor caracteristice și a rezultatelor inspecției în cadrul unui model Knowledge Graph pentru a sprijini luarea deciziilor.