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The Concept of a Digital Twin for the Wały Śląskie Hydroelectric Power Plant: A Case Study in Poland

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Abstract: This paper introduces a conceptual framework for the development and implementation of a digital twin specifically designed for the Wały Śląskie Hydroelectric Power Plant. The primary focus is on defining the digital twin concept, addressing critical challenges encountered during its conceptualization, such as incomplete plant documentation, limited real-time data availability, and complexities in system integration. The digital twin architecture developed to address these issues features modular components, including data acquisition, data processing, visualization, and integration layers, emphasizing scalability, adaptability, and secure interoperability. Computational Fluid Dynamics (CFD) simulations and AI-based modeling techniques are integrated into the proposed framework as essential tools, providing critical data inputs for efficiency modeling and operational analysis. The proposed digital twin concept ensures accurate and reliable digital representation, facilitating informed decision-making and efficient operational management within hydropower plants.

Keywords: digital twin; hydropower; modular architecture; system architecture

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1. Introduction

Hydropower plays a crucial role in global renewable energy generation, providing a stable and reliable source of electricity compared to intermittent energy sources such as wind or solar power. In 2020, global hydropower capacity increased to 1330 GW, and the sector generated a record 4370 TWh of clean electricity, highlighting its importance in the decarbonization of the economy [1]. According to EU regulations, hydropower is set to be the cornerstone of the climate neutrality strategy by 2050 [2]. In the 21st century, significant failures of hydropower plants have been recorded, caused by insufficient control systems and neglect in operation and maintenance (O&M). Examples include the following:

- The failure at the Taum Sauk Hydroelectric Power Station in 2005, where damage to indicators and inadequate control systems led to water overflowing the crest of the upper reservoir dam, causing the embankment to collapse and resulting in the loss of over 4 million cubic meters of water in less than 30 min;

- The failure at the Sayano–Shushenskaya Dam in 2009 resulted in the tragic loss of 75 lives, primarily due to negligence in operation and maintenance (O&M). Poor maintenance practices caused vibrations in Unit 2 (one of ten turbines), leading to the failure of the head cover bolts. This ultimately triggered the flooding of the machine hall and the explosion of two generators, resulting in a loss of 6 GW of power [3].

The advanced development of digital technologies enables increasingly effective monitoring and prediction of hydrotechnical structures, significantly enhancing energy security by minimizing the risk of blackouts and improving the operation of facilities and their immediate surroundings. A widely adopted approach is the implementation of a digital twin (DT), a technology that integrates a physical object, its digital representation, and the dynamic interactions between them. This adaptability allows for rapid responses to operational changes and failures while providing a safe virtual environment for testing new system solutions and optimizing processes. Furthermore, data generated by the digital model supports advanced technological and engineering workflows across various stages of the lifecycle of the facility and its components [4–9]. A detailed discussion of selected references is presented later in the article.

Ghenai Ch. et al. [5] highlight key challenges in implementing digital twins (DTs), such as the need for fast connectivity, high computational power, cybersecurity, and costs associated with the lifecycle of physical assets. In the context of energy storage systems, DTs support the creation of optimal charging and discharging schedules, leading to energy cost savings [10]. Additionally, study [11] indicates DTs can contribute to modernizing hydropower plants by enabling automated management and remote operation, significantly improving their operational efficiency.

In publications [8,9], the authors outline key functions by DTs, including real-time synchronization between physical systems and their digital counterparts, the implementation of predictive maintenance strategies, and data-driven decision-making for performance optimization. According to [8], DTs have significant potential to transform hydropower operations, reduce costs, and enhance system reliability. However, challenges in their implementation include the complexity of creating precise models, integrating supporting technologies, and ensuring efficient real-time data communication. Tao F. et al. (2019) [9] emphasize the need for standardized methods and tools for effective DT deployment in the renewable energy sector, especially in hydropower. Interoperability and scalability remain significant barriers, limiting the widespread adoption of this technology in energy systems.

Zhao Z. et al. [12] presented DTs as data-driven systems that leverage artificial intelligence and machine learning to model the nonlinear and complex dynamics of hydropower systems. A key innovation is a multi-layered architecture encompassing data acquisition, model development, and operational applications. The authors emphasize the scalability and adaptability of the solution, which allows it to meet future challenges in the energy sector.

Cai Z. et al. [13] introduced an innovative approach to DT operation by integrating RFID (Radio Frequency Identification) technology with Adaptive Time-Frequency Memory (AD-TFM) neural networks for real-time fault detection. The combination of RFID and AD-TFM demonstrated improved accuracy and efficiency in fault detection. Tests conducted at the Yangxia 2 hydropower plant confirmed the high effectiveness of the solution, which increased operational efficiency by 10–15%. Expanding the scope to include the identification of other fault types and incorporating real operational data remains a crucial area for further development.

The research presented in [14] was conducted in a pilot laboratory at the Norwegian University of Science and Technology (NTNU), using adaptive machine learning mechanisms that combine physical modeling with data-driven approaches (e.g., shaft speed, water head, and torque). A recursive adaptive learning mechanism, employing a least-squares algorithm, achieved a minimal error (<1%) in turbine performance simulations, demonstrating the solution's effectiveness in real-world applications.

The experimental results described by Ersan M. et al. [15] showcase the implementation of a DT at a hydropower plant in Turkey with 2 × 625 kW units. The model, integrated with PLC and SCADA systems, enables monitoring of a selected parameter—pressure—and supports predictive maintenance, significantly increasing reliability and operational efficiency. Despite challenges related to DT calibration and adaptation, the authors highlight the potential for extending the technology to other system components.

Publication [16] describes the application of reinforcement learning (RL) algorithms in hydropower systems using a DT platform. DT technology enables pre-training RL algorithms on historical data, testing them in virtual environments, and adapting them to physical systems through transfer learning (TL). This approach enhances RL reliability and efficiency while reducing training time and minimizing operational risks. The technology shows potential for improving the flexibility and efficiency of pumped-storage hydropower plants. The authors plan further work on applying RL to real-world systems and more complex operational scenarios.

In the context of Industry 4.0, the authors of publication [17] emphasize the importance of the digitization and standardization of DTs to achieve sustainable development goals in hydropower. Future research should focus on addressing implementation barriers, such as cybersecurity and data integration, to facilitate the broader adoption of this technology.

DTs represent a critical tool for optimizing and managing hydropower systems, combining physical modeling with advanced machine learning and predictive algorithms. Research findings demonstrate their effectiveness in both research laboratories and real-world facilities, enabling real-time monitoring, predictive maintenance, and testing of new solutions in a virtual environment. In the context of Industry 4.0, DTs play a vital role in transforming the hydropower sector, supporting sustainable development goals.

The D-HYDROFLEX project is developing a comprehensive suite of digital tools aimed at enhancing the flexibility and sustainability of hydropower plants across Europe. These tools are being tested at various demonstration sites to ensure their effectiveness in different operational environments. Below is an overview of the tools, their functionalities, demonstration sites, and the teams responsible for their development (Table 1).

The D-HYDROFLEX consortium comprises seventeen partners from seven European countries, including five power plant operators/energy producers, six European research institutes and universities, and seven technology providers. This multidisciplinary collaboration ensures that the developed solutions are robust, scalable, and applicable across diverse operational contexts.

This publication focuses on the conceptual design of the Hydro Unit Digital Twin for the Wały Śląskie Hydroelectric Power Plant. Developed as part of the D-HYDROFLEX initiative, this digital twin framework incorporates multiple specialized modules to address challenges in monitoring, maintenance, and operational optimization. Below is an overview of the tools under development:

1. HYDRO-TIN is designed to assess turbine efficiency by processing data such as flow rate, water levels, rotational speed, and blade angles. The concept includes efficiency curve generation and a comparison of measurements with model predictions to support the optimization of turbine performance;
2. HYDRO-MAP proposes a four-stage approach to hydrological modeling and forecasting using gauge station data and LSTM neural networks. This framework aims to predict water flow variations, enabling proactive operational planning and more efficient resource management;

3. CFD Analysis, initially conceived as HYDRO-CFD and now integrated with HYDRO-VIS, provides access to pre-computed CFD simulation results showing flow patterns, pressure distributions, and velocity vectors within turbine components. The design includes provisions for future refinement through 3D scanning of actual turbine geometry;
4. HYDRO-PVIL presents a multi-level approach to vibration monitoring and analysis, beginning with basic threshold-based alerts (Level 0) and outlining a pathway toward advanced predictive maintenance capabilities. The framework aims to enhance reliability through early detection of mechanical anomalies;
5. HYDRO-VIS functions as the central visualization interface, integrating data from all other tools to provide operators with actionable insights. The concept includes interactive dashboards, time-series analysis tools, and specialized visualizations for efficiency monitoring and CFD results exploration.

Table 1. Overview of D-HYDROFLEX tools, demonstration sites, and development teams.

Tool	Demonstration Site(s)	Development Team(s)	Description
Hydro Unit Digital Twin	Wały Śląskie HPP, Poland	Wrocław University of Science and Technology (PWR)	Mirrors the turbine set, visualizes sensor data, and integrates condition monitoring into a digital model to facilitate monitoring and maintenance processes.
Fault Detection and Predictive Maintenance System	Kremasta and Ilarion HPPs, Greece	Public Power Corporation (PPC), Greece	Utilizes data from various sources, including vibration measurements and SCADA data, to detect abnormalities and predict maintenance needs, thereby reducing unplanned downtime.
Cloud-Based Monitoring and Diagnostics Center	Multiple sites across Europe	UBITECH ENERGY	Provides remote, real-time insights into overall plant operations, identifying sources of unplanned downtime and process inefficiencies. Serves as the backbone for integrating all D-HYDROFLEX tools, supporting their setup at demonstration sites and ensuring replicability and scalability.
AI-Based Dam Digital Twin Framework	To be determined	Consortium of technology providers within D-HYDROFLEX	Automatically generates a digital twin model of a dam by capturing spatial and visual data on-site, as well as importing, registering, and integrating data, to enhance monitoring and maintenance.
Hydropower 4.0 Toolkit	Multiple sites across Europe	UBITECH ENERGY	Facilitates real-time system management and remote monitoring, supporting plant operators in participating in wholesale power markets and increasing operational efficiency. Includes a dashboard with interactive capabilities providing targeted information to hydropower plant operators.

Together, these modular components form a comprehensive digital twin framework that aims to enhance monitoring capabilities, enable proactive maintenance, and support data-driven operational decisions. The scalable architecture is designed to accommodate progressive implementation and future expansion, aligned with the broader objectives of the D-HYDROFLEX project.

2. Materials and Methods

2.1. Water Power Plant Description

The Wały Śląskie Hydropower Plant (HPP) is a run-of-river facility strategically positioned at kilometer 281 + 600 on the right bank of the Odra River. It forms an integral part of the energy and shipping dam at Brzeg Dolny, serving dual functions of navigation support and energy production since its commissioning in 1958. The plant currently maintains a Normal Retention Level of 107.50 MASL, which was adjusted downward from the original 108.00 MASL in 1993. This water impoundment creates a substantial river valley reservoir spanning 5.25 km^2, with a total capacity of approximately 14 million m^3, of which 6.0 million m^3 represents usable capacity between levels 106.80 and 107.50 MASL.

At the heart of the facility are four Kaplan turbine hydro sets with vertical axes, each featuring a rotor diameter of 4.0 m. These turbines are comprehensively equipped with speed regulators, pump aggregates, and servomotors for the guide apparatus. The generators, manufactured by CKD Praha and CKD Blansko, are housed within a monolithic reinforced concrete construction. Each individual turbine operates with a nominal discharge of 60 m^3/s under a nominal head of 4.70 m, delivering 2.43 MW of power. Collectively, these units provide the plant with a total installed capacity of 9.72 MW and a maximum installed discharge of 240 m^3/s.

Before the implementation of the D-HYDROFLEX project, the plant relied on basic monitoring equipment, including vibration sensors, rotational speed sensors, guide vane position sensors, turbine blade position sensors, electrical value meters at generator outputs, and temperature sensors for the hydro units. Despite this instrumentation, the facility faced significant limitations in data management and operational optimization. Most parameters were not being recorded, and readings were displayed at multiple disconnected locations throughout the plant without unified software. The existing measurement infrastructure required thorough verification due to concerns about service life and operational reliability.

The Wały Śląskie HPP holds considerable operational significance within the regional energy infrastructure. Until the construction of the Malczyce Dam in 2018, it represented the last dam on the canalized river designed for navigation purposes. The plant is managed by TAURON Ekoenergia sp. z o.o., while the Regional Water Management Authority (RZGW) in Wrocław oversees water management and maintenance responsibilities. Although the plant's theoretical production potential is calculated at 47,984.7 MWh annually, its actual performance typically falls approximately 5% below this figure, highlighting opportunities for efficiency improvements through the D-HYDROFLEX digital twin implementation.

The facility's position on the Odra River—Poland's second-longest river, with a basin covering 124,049 km^2 across Poland, the Czech Republic, and Germany—underscores its importance in both the regional energy landscape and the broader river navigation system. Through the D-HYDROFLEX project's digital twin implementation, the plant aims to optimize operations, enhance maintenance protocols, and maximize energy production from the existing infrastructure without negative environmental impacts.

2.2. Initial Steps and Approach to Digital Twin Preparation

The development of a digital twin for the Water Power Plant (WPP) required a systematic approach to address the unique challenges posed by the existing infrastructure, operational demands, and limited initial data availability. The preparation phase included detailed site assessments, stakeholder consultations, and strategic planning to ensure the feasibility and alignment of the digital twin with the plant's operational goals.

The project began with on-site visits to the WPP to evaluate the existing infrastructure and systems. These assessments focused on the following:

- Identifying the installed measurement devices;
- Evaluating the need for additional instrumentation;
- Documenting the current data acquisition setup and assessing its integration capabilities with modern systems.

This groundwork provided a clear picture of the plant's capabilities and the modifications required to create a comprehensive digital twin. Similar approaches to infrastructure evaluation in digital twin projects can be found in the literature, where site-specific constraints significantly influence the design process [18].

Collaboration with the plant's operators and stakeholders, including Tauron, played a pivotal role in defining the system architecture. The key discussions included the following:

- Determining data acquisition protocols, such as the adoption of Modbus TCP/IP for integrating sensors with the data acquisition system and supervisory computers;
- Addressing the IT/OT boundary to ensure secure and reliable communication between operational systems and the planned digital twin, with a focus on network safety and data integrity;
- Outlining the scope of the digital twin, including its primary focus on efficiency modeling, predictive maintenance, and data visualization.

This collaborative approach aligns closely with the case study presented by Jones et al. [19], which highlights how stakeholder engagement and iterative integration processes were critical in the implementation of a digital twin for a German multinational manufacturing company. The study emphasizes the importance of balancing technical innovation with operational requirements to ensure the digital twin's adoption and functionality. By engaging stakeholders early and defining clear protocols and responsibilities, the project aimed to create a cohesive system architecture that supports the digital twin's objectives while ensuring security and operational efficiency. These consultations not only shaped the technical requirements but also helped align the digital twin's functionality with the plant's long-term operational strategy.

The process of developing a digital twin involves iterative refinement and validation to ensure alignment with operational requirements. Figure 1 illustrates the workflow.

It begins with the identification of requirements and assessment of existing sensor systems. If gaps or inadequacies are found, additional sensors or upgrades are installed to ensure data availability and compatibility. The core of the process is a cyclical loop of model development, data integration, and performance validation. This iterative loop addresses inaccuracies and refines the system until it meets predefined accuracy requirements. Once validated, the system proceeds to final integration, resulting in a digital twin ready for deployment.

Validation challenges revolve around ensuring the digital twin accurately mirrors the physical system under various operational scenarios. This often requires iterative refinement cycles, where discrepancies between simulated and real-world data are addressed.

Tao F. et al. [20] outlined the importance of iterative validation to build robust and reliable digital twins. Wynn and Irizar [19] described techniques for refining models based on feedback from operational systems. Ghenai et al. [5] further highlighted the role of simulated scenarios in validating digital twins when live operational data are limited.

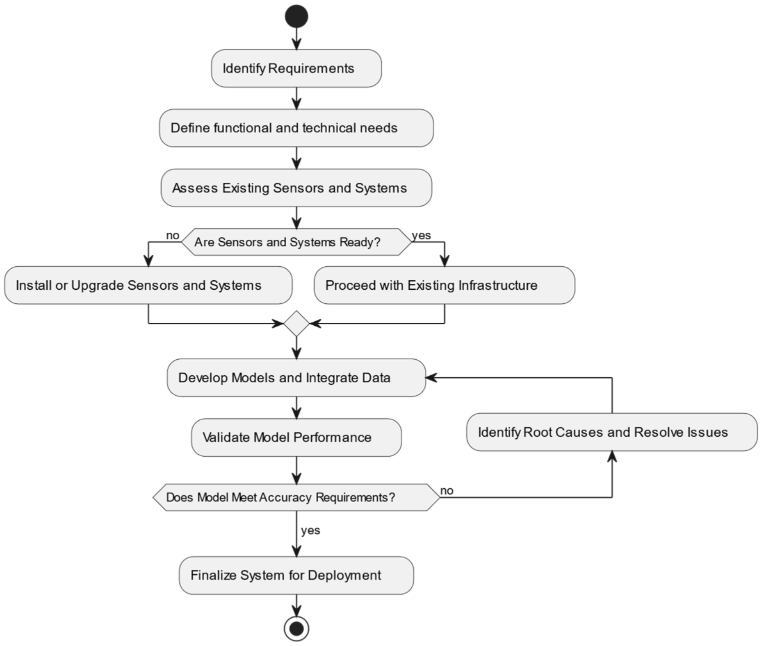

Figure 1. Digital twin development process.

2.3. Challenges and Solutions in Digital Twin Development

The process of creating a digital twin for the Wały Śląskie Water Power Plant (WPP) presented a variety of challenges, ranging from infrastructure limitations to technical complexities. These obstacles arose due to incomplete documentation, the limited availability of real-time data, and the intricacies of integrating diverse systems. The team addressed these issues systematically through tailored solutions and iterative processes, ensuring alignment with the operational goals of the plant.

The challenges encountered during the project can be categorized into infrastructure, data, technical, and validation-related issues. Each category reflects the complexity of creating a digital twin for a legacy hydropower plant. A summary of these challenges and the relevant literature is presented in Table 2.

Table 2. Overview of challenges during digital twin development with examples from literature.

Challenge Type	Description	Examples from Literature
Infrastructure	Limitations in systems, instrumentation, or documentation hindering modeling accuracy.	[11,13,19,20]
Data	Issues with availability, quality, or completeness of required datasets.	[5–7]
Technical	Integration of sensors and systems, ensuring secure communication, and calibration challenges.	[13–15]
Validation	Ensuring model accuracy and alignment with the physical system through iterative processes.	[10,16,18]

Infrastructure challenges often stem from outdated systems, incomplete documentation, or a lack of modern instrumentation. These issues delay the development process and require significant updates to the plant's infrastructure. Tao F. et al. [20] emphasized that outdated legacy systems can impede digital twin implementation, as their research identified issues with isolated, fragmented, and stagnant data in product lifecycles without proper convergence between physical and virtual spaces. Wynn and Irizar [19] highlighted the importance of addressing technology integration issues to create reliable linkages between systems, stressing the need for comprehensive documentation and infrastructure updates to support digital twin development. Vagnoni et al. [11] examined the role of digitalization in the hydropower sector, noting that while digitalization technologies offer strategic benefits for balancing environmental, economic, and social aspects, their research revealed uneven adoption of digital technologies across European hydropower facilities, creating implementation challenges. Additionally, Cai et al. [13] explored the difficulties of integrating modern fault detection systems into existing hydropower infrastructure, identifying how complex interior structures complicate inspection processes and proposing solutions using RFID technology and deep learning models to overcome these infrastructure limitations in digital twin implementation.

Data challenges encompass issues with availability, quality, or completeness of required datasets essential for digital twin development. These challenges significantly impact model accuracy and reliability. Hashmi et al. [7] investigated digital twins for renewable energy systems, highlighting that while there is strong theoretical support for digital twins to optimize these systems, practical implementation faces significant barriers due to limited access to real-time data, creating a gap between theoretical understanding and real-world application. Ismail et al. [6] conducted a comprehensive review of digital twin applications across diverse energy sectors, noting that data quality and availability represent significant implementation challenges, as the effectiveness of digital twins depends on accurate and up-to-date data for simulations and predictions. The authors emphasized that insufficient, outdated, or poor-quality data can compromise digital twin accuracy, and limited access to real-time data further restricts effectiveness. Additionally, Ghenai et al. [5] reviewed digital twin technologies in the energy sector, identifying several data-related challenges, including the need for standardized data models, high computing power for real-time data processing, and security concerns around the accumulation of sensitive operational data, all of which must be addressed to maximize the potential of digital twins in energy applications.

Technical challenges involve integrating diverse sensors and systems, ensuring secure data communication, and addressing calibration complexities to maintain the accuracy and reliability of digital twin models. Wang et al. [14] addressed these issues by implementing adaptive learning algorithms capable of the real-time calibration of digital twin models, effectively enhancing the accuracy and responsiveness of hydropower turbine simulations. This adaptive approach combined physical models with recursive least squares algorithms to dynamically update system parameters, reflecting real-world operational variations and improving overall model reliability. Similarly, Ersan and Irmak [15] developed a digital twin model specifically targeting sensor anomaly detection, emphasizing the critical role of precise and reliable sensor data. Their work demonstrated how advanced digital twin algorithms could differentiate between genuine equipment malfunctions and measurement or communication errors, significantly reducing unnecessary shutdowns and enhancing operational continuity. Additionally, Cai et al. [13] employed RFID technology and deep learning techniques, including adaptive Time–Frequency Memory models, to efficiently handle fault detection in complex hydropower environments. Their approach highlighted how integrating modern identification and machine learning methods can overcome technical challenges related to data acquisition and processing, significantly improving fault prediction accuracy and reliability.

Validation challenges involve rigorous processes to ensure the digital twin accurately reflects real-world conditions and plant behavior through iterative testing and refinement. Grieves and Vickers [18] emphasized that meticulous validation is critical to mitigating unpredictable, potentially catastrophic emergent behaviors in complex systems. They highlighted digital twins' capacity to conduct comprehensive pre-deployment simulations, enabling the early identification and correction of system vulnerabilities. Similarly, Tubeuf et al. [16] demonstrated how reinforcement learning combined with digital twin platforms effectively enhanced the operational flexibility and reliability of hydropower systems. Furthermore, Park et al. [10] showed the application of digital twins specifically for rotating machinery fault detection, underscoring how digital twins provide effective tools for real-time diagnostics, early fault prediction, and operational validation, thus reducing risk and improving asset management.

To address the infrastructure challenges at the Wały Śląskie WPP, several solutions were implemented. First, a 3D model of the Kaplan turbine—based on existing technical specifications—was created to support CFD simulations until future renovation permits a full 3D scan. In parallel, the project team leveraged the plant's existing measurement system wherever possible and introduced additional components, as needed, to facilitate a comprehensive digital twin. One of the most notable additions is the Winter–Kennedy flow measurement method, which relies on differential pressure measurements within the turbine's casing. This approach is particularly appealing because it uses pre-existing pressure taps, making it easier and more cost-effective than installing large-diameter flow meters. Since full-scale flow meters can be prohibitively expensive and difficult to integrate into a running plant, the Winter–Kennedy method provides a practical alternative. Calibration of these measurements is conducted using custom-built velocity propeller meters, ensuring that the recorded differential pressures accurately reflect actual flow rates. Finally, a modular sensor architecture was designed to allow phased upgrades without requiring extensive, simultaneous modifications to the plant.

Data challenges were managed through multiple approaches. CFD simulations were used to generate comprehensive efficiency curves that compensate for the initial lack of empirical performance data. The HYDRO-MAP framework proposes methodologies for processing gauge station data, including quality checks, gap identification, and interpolation techniques. LSTM neural networks were proposed as part of the architecture to address the complexities of flow prediction with limited data by learning from temporal patterns in hydrological time series.

For technical challenges, the architectural design proposes integrating existing analog signals and digital protocols (such as Modbus) with additional industry-standard communication protocols to ensure reliable data transfer between field devices and higher-level systems. The concept includes a hierarchical architecture separating operational technology (OT) and information technology (IT) components to enhance security while enabling efficient data flow. The HYDRO-VIS component design incorporates data integration mechanisms that standardize diverse formats from multiple sources for coherent presentation and analysis.

The validation approach proposes a phased implementation beginning with basic monitoring capabilities, allowing for the validation of fundamental functionality before advancing to more complex features. The HYDRO-TIN design includes mechanisms for comparing measured efficiency values with model predictions, enabling continuous validation and refinement of the efficiency curves. For vibration monitoring, ISO 10816-5 standards [21] are proposed as validation benchmarks. All components include provisions for model updates based on operational data, allowing the digital twin to evolve and improve in accuracy as more real-world data becomes available.

3. Results

3.1. System Architecture

The architecture of the digital twin provides a structured framework for comprehensive monitoring, analysis, and operational decision-making support. It integrates multiple data streams, including real-time sensor data, historical information, predictive analytics, and simulation results. The architecture consists of the following components (Figure 2):

- Data Acquisition Layer: Collects and transmits operational parameters such as flow rates, water levels, turbine blade angles, rotational speeds, and vibration data through standardized protocols like Modbus TCP/IP;
- Data Processing Layer: Analyzes raw sensor data to calculate derivative parameters such as turbine efficiency, predictive maintenance indicators, and operational forecasts using specialized tools like HYDRO-TIN and HYDRO-PVIL;
- Visualization Layer: Provides operators with intuitive, real-time insights via interactive dashboards, detailed charts, and advanced 3D visualizations, facilitating effective monitoring and decision-making;
- Integration Layer: Ensures seamless communication among the various digital twin components, external data sources (e.g., CFD simulations), and hydrological predictions, maintaining interoperability, scalability, and security.

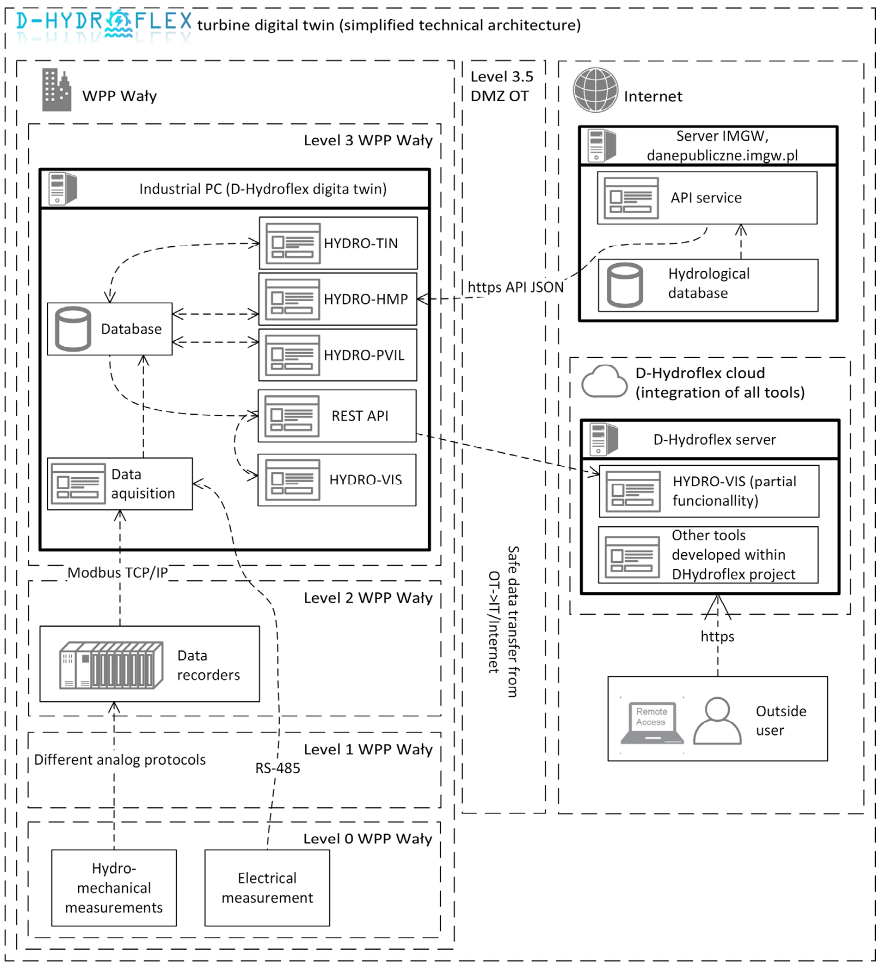

Figure 2. D-Hydroflex turbine digital twin architecture.

This modular design ensures the architecture is adaptable and scalable, supporting incremental enhancements and future expansions.

3.2. Concept of Developed Tools

3.2.1. HYDRO-TIN

The HYDRO-TIN module establishes a framework for real-time turbine efficiency monitoring through comparative analysis between observed and theoretical performance metrics. The conceptual design implements three sequential processing stages to assess the operational performance of the Kaplan turbine installation at Wały Śląskie Hydropower Plant, as illustrated in Figure 3.

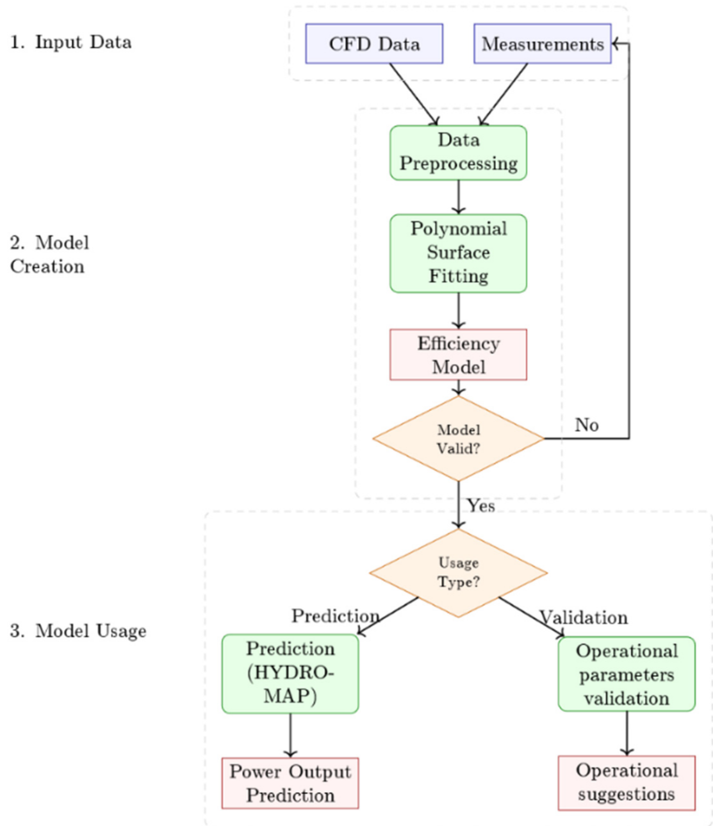

Figure 3. Conceptual workflow of the HYDRO-TIN module.

In the data acquisition stage, the system incorporates dual input streams comprising CFD simulation results and field measurements. The initial implementation prioritizes CFD-derived performance characteristics while establishing the requisite field instrumentation infrastructure for empirical data collection.

The model creation stage implements polynomial surface fitting algorithms to generate parametric efficiency models based on turbine unit flow and unit speed indicators. These mathematical representations utilize polynomial surfaces as the initial modeling approach, having demonstrated strong fitting characteristics with existing Kaplan turbine datasets. The polynomial technique enables efficient representation of the complex, multi-dimensional relationships between operational parameters and efficiency values across the turbine's operational envelope. Should the Wały Śląskie turbine exhibit efficiency characteristics that cannot be adequately represented by polynomial surfaces, the system architecture allows for the implementation of alternative modeling approaches such as spline surfaces (similar to NURBSs—Non-Uniform Rational B-Splines) that offer greater flexibility in capturing complex topological variations in the efficiency landscape. This adaptive approach ensures robust model performance regardless of the specific characteristics exhibited by the particular turbine installation.

During the operational stage, HYDRO-TIN continuously monitors critical parameters, including volumetric flow, head conditions, and power generation. The system performs real-time comparative analysis between measured performance metrics and model-predicted values, calculating efficiency deviations that serve as key indicators of turbine health and performance optimization opportunities.

The HYDRO-TIN module functions as an independent efficiency modeling system, generating detailed turbine performance models that can be utilized by other components within the Digital Twin framework, including HYDRO-HMP for power estimation. While providing efficiency models to other modules, HYDRO-TIN operates autonomously, requiring no input from these systems for its core functionality. The resulting efficiency metrics are supplied to HYDRO-VIS for operator visualization, enabling informed operational decision-making and identification of performance optimization opportunities.

3.2.2. HYDRO-MAP

The HYDRO-MAP concept represents a hydrological modeling and flow prediction framework for integration within the Hydro System Digital Twin at the Wały Śląskie Hydropower Plant. As illustrated in the simplified workflow diagram (Figure 4), HYDRO-MAP employs a four-stage sequential process:

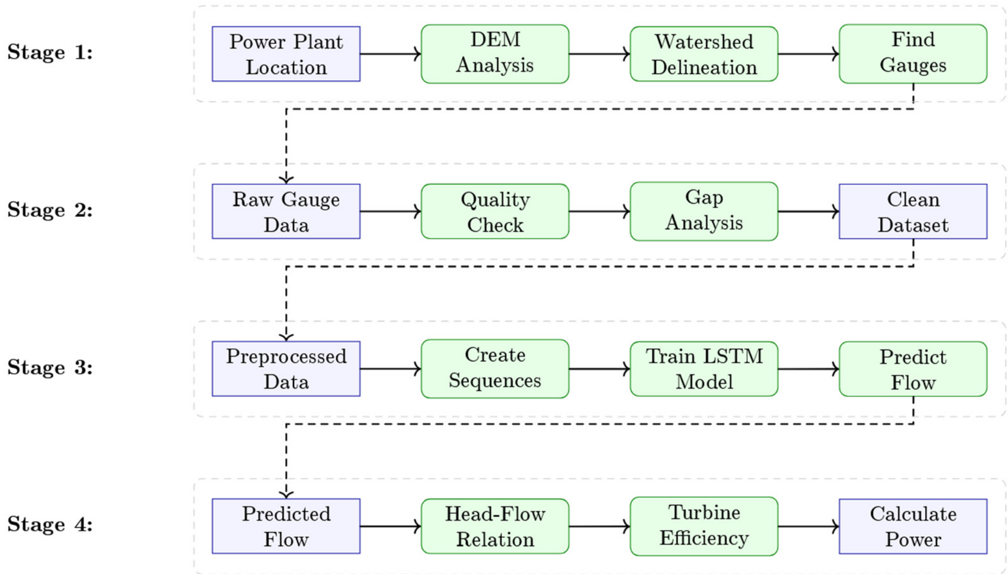

Figure 4. Workflow of the HYDRO-MAP module.

Stage 1—Watershed Analysis: Beginning with power plant location data, this stage utilizes Digital Elevation Model (DEM) data from the Copernicus Global Digital Elevation Model (CGDEM) to perform terrain analysis. The process delineates watershed boundaries and identifies water gauge stations within this area for subsequent data collection.

Stage 2—Data Processing: This stage performs quality assessment of gauge station data, identifies measurement gaps, and applies appropriate interpolation techniques to ensure data continuity. The output is a cleaned, structured dataset optimized for computational modeling.

Stage 3—LSTM Model Implementation: The framework employs Long Short-Term Memory (LSTM) neural networks for water flow forecasting. The model processes preprocessed hydrological time series data collected at 10 min intervals, stored in the Parquet format. This stage handles sequence creation, model training, and flow prediction functions.

Stage 4—Power Estimation: The final stage calculates potential power generation based on predicted flow data. The computation incorporates head–flow relationships, operational constraints, and turbine efficiency parameters from the HYDRO-TIN module.

The HYDRO-MAP concept addresses several key operational requirements for hydropower management:

- Flow prediction at various time scales;
- Operational planning support through anticipatory flow data;
- Data-driven turbine scheduling optimization;
- Adaptive operation during changing hydrological conditions.

According to the system architecture design, all HYDRO-MAP outputs integrate with the HYDRO-VIS interface to provide operators with actionable decision support information.

3.2.3. HYDRO-PVIL

The HYDRO-PVIL tool functions as a vibration monitoring and analysis system within the Hydro System Digital Twin for the Wały Śląskie Hydropower Plant. It follows a multi-level approach to machine condition assessment, with the initial focus on Level 0 capabilities as a foundation for future expansion.

HYDRO-PVIL continuously monitors vibration data, detects threshold exceedances, and enables operators to take proactive maintenance measures. The system complies with the ISO 10816-5 standard [21], under which the analyzed Kaplan turbine is classified as Group 4.

The Core components include the following:

- A Vibration Monitoring System: This acquires displacement and velocity measurements from sensors installed at critical locations, such as shaft bearings and structural supports;
- A Threshold Alert Framework: This triggers alerts when vibration amplitudes exceed predefined limits set according to the ISO 10816-5 [21] operational zones (A through D);
- A Data Analysis Interface: This offers the visualization of current vibration states and historical trends to assess machine conditions over time.

The modular architecture of HYDRO-PVIL allows for incremental feature integration at four defined levels, illustrated in Figure 5:

- Level 0 (Initial Implementation): Basic vibration amplitude monitoring with threshold-based alerts for the early detection of potential issues;
- Level 1 (Future Expansion): Incorporates FFT spectral analysis and orbit plot visualization for enhanced diagnostic capabilities;
- Level 2 (Future Expansion): Introduces advanced shaft condition monitoring with additional sensors, shaft deflection modeling, and fatigue assessments;
- Level 3 (Future Expansion): Employs AI-driven predictive maintenance to reduce human intervention, including remaining time-to-failure estimation and automated service recommendations.

By enabling the early detection of mechanical anomalies before they escalate into failures, HYDRO-PVIL supports strategic maintenance planning and enhances plant reliability. The system also interfaces with HYDRO-VIS for data visualization and condition reporting.

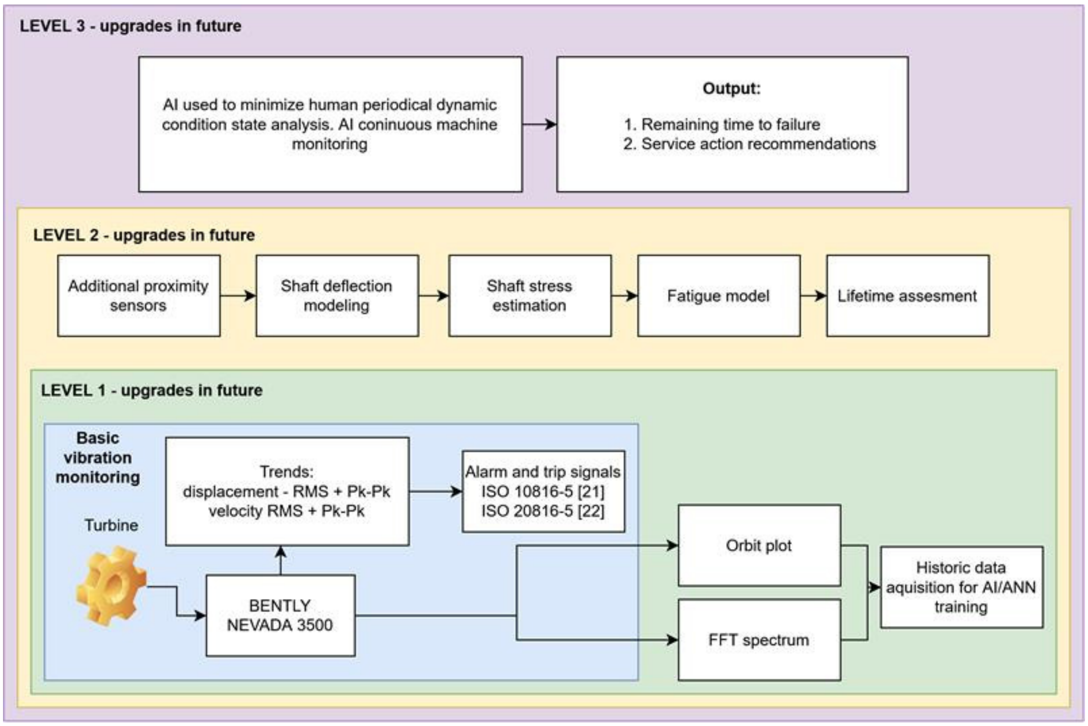

Figure 5. Modular architecture of the HYDRO-PVIL system [21,22].

3.2.4. CFD Analysis Integration with HYDRO-VIS

Computational Fluid Dynamics (CFD) analysis is a foundational component of the Hydro System Digital Twin for the Wały Śląskie Hydropower Plant. Originally developed as a standalone tool called HYDRO-CFD, it was later integrated as a functional module within HYDRO-VIS due to computational resource constraints.

This integration grants access to a repository of pre-computed CFD simulations that model Kaplan turbine flow behavior under various operating conditions. The simulations provide detailed insights into flow patterns, pressure distributions, and velocity vectors throughout turbine components, including the spiral inlet, guide vanes, impeller, and draft tube.

The core components include the following:

- A CFD Simulation Database: A repository of pre-computed results covering different operational conditions (heads, flows, guide vane angles, and impeller blade positions) used as a basis for the HYDRO-TIN efficiency model;
- A Results Browser: An interface (implemented as part of HYDRO-VIS) that allows users to select parameters and visualize corresponding simulations without requiring real-time CFD computation.

By enabling the analysis of flow structures at various operating regimes and identifying hydraulic inefficiencies, the integrated system helps operators better understand turbine behavior. The CFD data directly support the HYDRO-TIN turbine efficiency model by detailing flow characteristics and energy losses under different conditions, thus enabling accurate efficiency–curve construction and comprehensive performance analysis. The database framework is designed to accommodate expansion with additional pre-computed scenarios as needed.

3.2.5. HYDRO-VIS

The HYDRO-VIS module serves as the primary visualization and data presentation component within the Hydro System Digital Twin framework for the Wały Śląskie

Hydropower Plant. It functions as a central interface for displaying operational data, computational results, and predictive outcomes produced by other system modules.

HYDRO-VIS integrates data from multiple sources—including digital twins (HYDRO-TIN), fault prediction tools (HYDRO-PVIL), CFD simulations, and hydrological analyses (HYDRO-MAP)—and converts this information into clear visual formats to support operator decision-making.

The core components include the following:

- A Data Integration Framework: This collects and processes data from various system modules, creating a unified data structure for visualization;
- An Interactive Dashboard: This displays critical operational parameters (e.g., water flow, turbine blade angles, rotational speeds, and power output) through customizable interfaces;
- Time-Series Analysis Tools: These allow operators to review historical trends, compare current performance to past baselines, and visualize deviations from expected parameters;
- Turbine Efficiency Visualization: This plots real-time operational points against computed efficiency curves, helping operators identify optimal operating conditions and detect performance deviations;
- A CFD Results Browser: This offers pre-computed CFD simulations for users to explore flow patterns, pressure distributions, and velocity vectors within turbine components under various operating conditions.

While the HYDRO-VIS concept currently focuses on Kaplan turbine operation—a principal goal of the D-Hydroflex project—it can be expanded to visualize multiple turbines or the entire hydropower plant. The system provides both real-time data and historical trends to provide operators with contextual insights into current operating conditions.

The key user interaction features include the following:

- Navigating between different visualization perspectives;
- Accessing detailed information on specific parameters;
- Tracking efficiency metrics under varying operating conditions;
- Reviewing maintenance alerts from HYDRO-PVIL;
- Examining CFD simulation data to understand complex flow phenomena within the turbine.

HYDRO-VIS functions as the interpretation layer between computational models and human operators, transforming complex data into actionable insights. By offering a clear visualization of system performance, efficiency patterns, and maintenance requirements, HYDRO-VIS supports both day-to-day operational optimization and long-term reliability management.

4. Conclusions

The conceptual design of the Hydro System Digital Twin for the Wały Śląskie Hydropower Plant addresses multiple challenges related to infrastructure, data acquisition, technical integration, and validation for the HYDRO-MAP, HYDRO-TIN, HYDRO-PVIL, and HYDRO-VIS frameworks.

The design compensates for the incomplete documentation of key components—particularly the Kaplan turbine—by proposing a virtual model based on known parameters. This approach employs CFD simulations to model flow behavior under various operational conditions, with the results integrated into the HYDRO-VIS browser concept. Provisions are made for future 3D scanning of the turbine, which would refine both CFD models and corresponding efficiency curves.

To overcome measurement limitations, particularly in flow monitoring, the concept incorporates the Winter–Kennedy flow measurement system. The proposed calibration of differential pressure transmitters using velocity propeller meters aims to supply data for the HYDRO-TIN efficiency monitoring module, enabling assessments of turbine performance against CFD-derived efficiency curves.

The HYDRO-MAP framework outlines a four-stage approach to hydrological modeling, processing available gauge station data, and utilizing LSTM neural networks for flow prediction. This design accommodates existing data constraints and allows for further enhancements as more operational data become available. Meanwhile, the HYDRO-PVIL concept presents a Level 0 implementation of vibration monitoring, with a clear pathway to more advanced diagnostic capabilities in later stages.

Industry-standard communication protocols, such as Modbus TCP/IP, facilitate data exchange among field sensors, acquisition systems, and the HYDRO-VIS visualization interface. This architecture helps maintain system integrity while ensuring operators have access to unified, real-time information.

Validation involves iterative refinement in each component. From the CFD analysis browser to the multi-level HYDRO-PVIL framework, the modular architecture allows for progressive implementation and enhancement based on evolving operational requirements.

Several avenues for future development have been identified: expanding HYDRO-MAP's flow prediction capabilities, further developing HYDRO-TIN efficiency modeling, advancing HYDRO-PVIL to higher analysis levels, and extending HYDRO-VIS to visualize multiple turbines or the entire power plant. The design also anticipates the integration of 3D-scanned turbine geometry to enhance simulation accuracy and operational insights.

By adopting a scalable, modular approach, this conceptual architecture can be adapted to other hydropower installations, thereby advancing the broader application of digital technologies within hydropower generation.

To maximize the effectiveness and replicability of the Hydro System Digital Twin, it is recommended that future implementations prioritize the early integration of standardized data acquisition systems and documentation practices. Establishing clear protocols for sensor calibration, data validation, and model updates will enhance long-term system reliability and comparability across installations. Additionally, fostering collaboration between hydropower operators, researchers, and technology providers can accelerate the development of modular diagnostic tools, such as advanced vibration analysis modules and AI-driven flow prediction systems. Investment in training for plant personnel on digital twin functionalities and decision-making based on simulation results is also advised to fully realize the operational benefits of the system.

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