Optimizing Hydropower Operations: A Tailored Digital Twin Framework For Hydropower Plant

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Abstract: Digital twins (DT) represent a critical methodology for digitising infrastructures, such as hydropower plants (HPP), enhancing their efficiency, sustainability, and competitive edge. However, despite the potential benefits, there is yet to be a consensus within industrial and academic spheres on the implementation process of digital twins for hydropower plants, a relatively uncommon type of infrastructure. This study explores the feasibility of using DT to provide digital solutions that enhance the flexibility and sustainability of hydropower plants. The paper examines the unique challenges associated with implementing digital twins in this context, including the high demand for water flow real-time updates, the complex logistical geographical dispersion, and environmental considerations. Subsequently, it reviews mainstream digital twin frameworks from other domains to establish foundational references. Building on this analysis, the study proposes a tailored digital twin development framework specifically tailored for hydropower plants. This proposed framework advances the theoretical understanding by integrating interdisciplinary research and domain-specific insights, offering a robust theoretical foundation for digital twin applications in hydropower settings. Practically, it delivers actionable guidelines and detailed strategies designed to facilitate the construction of digital twins in hydropower plants. By addressing domain-specific challenges and incorporating established best practices, the framework equips engineers and project managers with the tools necessary to enhance operational efficiency and sustainability. This comprehensive framework not only aids in navigating the complexities of hydropower projects but also sets a benchmark for future digital twin implementations.

Keywords: Digital twin, Hydropower plant, Implementation framework

1. INTRODUCTION

Digital twins (DT) have emerged as a pivotal technology for modernizing hydropower plants (HPP), bolstering their efficiency, sustainability, and competitive edge. This cutting-edge approach entails creating virtual models of physical hydropower facilities (Saif et al., 2024), allowing operators to simulate operations, anticipate potential issues, and implement solutions in a virtual space before applying them in the real world. The successful application of digital twins excelling in the building and construction sector where it aids in the lifecycle management of structures from design to demolition, ensuring optimal performance and maintenance.

However, as hydropower plants are a relatively rare type of infrastructure, the implementation of digital twins has not yet achieved widespread consensus within industry and academia. When developing digital twin frameworks, the HPP context presents unique challenges that set it markedly apart from conventional applications such as those found in building and construction (Cai et al., 2024). These distinctions arise primarily from the dynamic nature of water resources, the extensive regulatory environment, and the geographical dispersion of infrastructure—all intrinsic to the operation of hydropower facilities (Kumar et al., 2022). Unlike digital twins applied in more static or predictable settings, HPP digital twins must adeptly handle fluctuating natural inputs, adhere to stringent environmental standards (Couto & Olden, 2018), and manage complex, dispersed assets effectively (Azimov & Avezova, 2022). This fundamental differentiation underscores the necessity of a specialized approach tailored specifically for hydropower applications, as general digital twin models fall short of addressing the nuanced requirements of this sector.

This paper proposes a digital twin-based framework specifically tailored for HPP infrastructure by summarizing the experience of other existing types of digital twin systems and the unique domain characteristics of hydropower plants. From a theoretical perspective, this study introduces a novel Event-Driven Digital Twin (EDDT) framework specifically designed for hydropower plants, addressing the limitations of traditional layered DT architectures in dynamic, real-time environments. By leveraging event-based processing and decoupling system components, the framework enhances operational flexibility, scalability, and responsiveness in managing complex HPP operations. Practically, this research offers actionable strategies and a detailed framework that can be directly applied by engineers and project managers to enhance the efficiency, sustainability, and operational flexibility of hydropower plants. The proposed framework equips stakeholders with the tools necessary to overcome domain-specific challenges, thereby setting a benchmark for future implementations of digital twin technologies in similar infrastructure projects.

2. METHODOLOGY

The core of this research mainly includes three parts: review and summarise the architecture and experiments of existing DT frameworks in other fields, identify unique characteristics that may be encountered in DT implementation specifically under HPP scenarios, and propose a tailored DT framework combining the above experiences for HPP scenarios.

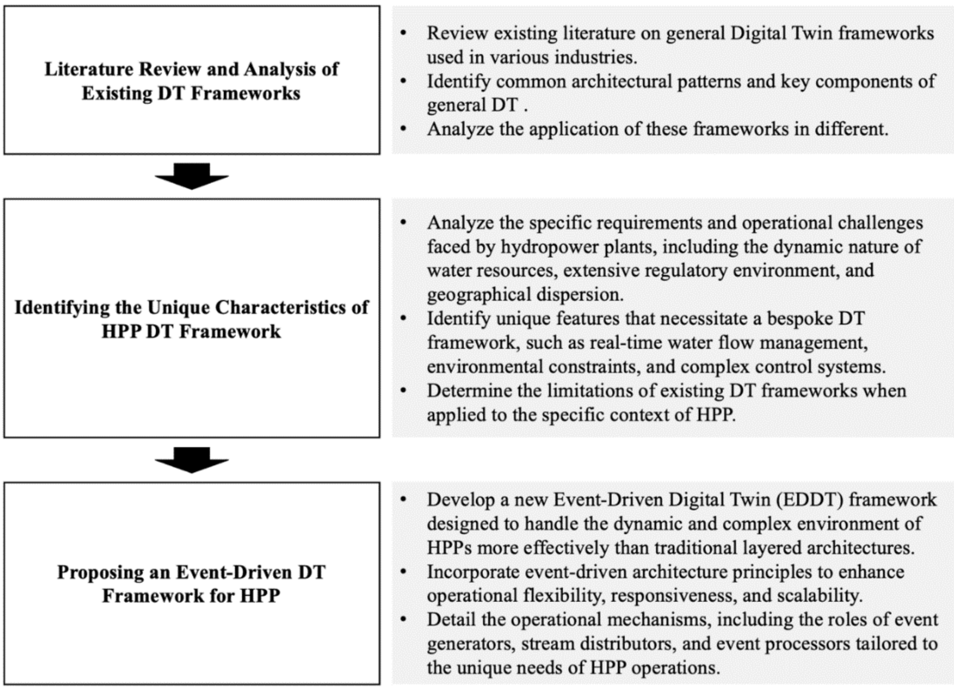

Figure 1. Research Methodology

As shown in Figure 1, the first step in the methodology involved a comprehensive review of existing literature on general DT frameworks, particularly those applied in industries such as manufacturing, construction, and energy management. The study focused on identifying common architectural patterns and key components of general DT systems, including data flow, modelling, simulation, and real-time control capabilities.

After identifying the limitations of general DT frameworks, the next step was to analyze the specific requirements and operational challenges faced by hydropower plants. HPPs have unique characteristics that distinguish them from other infrastructure types, such as dynamic water resource management, geographical dispersion, environmental and regulatory constraints (Zhang et al., 2014), complex operational requirements, integration with energy markets, and long asset lifecycles. This analysis highlighted the need for a more flexible and responsive DT framework that can handle these challenges, particularly in dynamic and highly regulated environments.

Based on the insights from the literature review and the specific requirements of HPPs, this study proposes an Event-Driven Digital Twin framework (EDDT) tailored to the unique needs of hydropower plants. The event-driven framework is particularly suited for hydropower plants because their operations are influenced by highly dynamic, real-time factors such as water flow and environmental conditions, which require immediate responses that traditional, sequential data processing frameworks cannot deliver with the same level of flexibility and speed (Cai et al., 2024).

3. RESULT

3.1 Existing DT framework

The mainstream general DT framework architecture in current research consists of the following layers: Physical Layer, Data Layer, Modeling Layer, Communication Layer, Analysis Layer, Application Layer, Security Layer, and Feedback & Control Layer (Zheng et al., 2019; Tuhaise et al., 2023; Aheleroff et al., 2021), as shown in Figure 2.

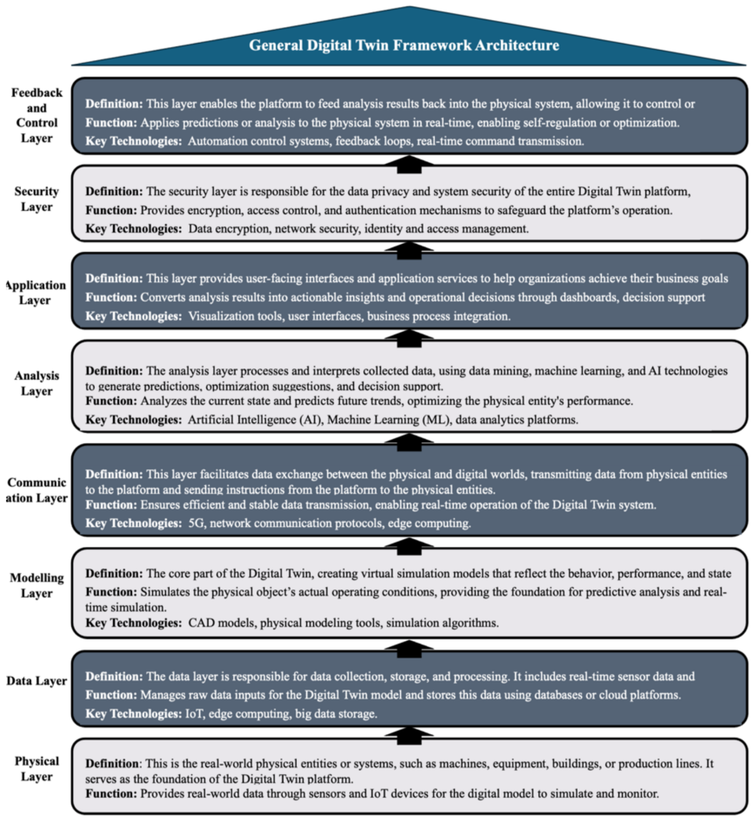

Figure 2. General digital twin framework architecture

The general digital twin framework architecture consists of multiple interconnected layers, each building upon the other to create a cohesive system that mirrors real-world physical entities in the digital space (Menon et al., 2023). The relationships between these layers are crucial to ensure the successful functioning of the digital twin, from data collection to real-time control and optimization.

Physical Layer forms the foundation of the system. It consists of the real-world physical assets, such as machines, infrastructure, or equipment, that are mirrored digitally. This layer is critical as it supplies the real-time data needed to accurately represent the physical world. The physical layer interacts directly with the **Data Layer** through sensors and IoT devices.

Data Layer collects and processes raw data from the physical assets. This layer ensures that the information coming from the physical world is gathered, structured, and stored in a way that can be further utilized by other layers. The data layer relies on **communication technologies**, such as the Internet of Things (IoT) and edge computing, to ensure that data flows efficiently from the physical world into the system.

Once the data is collected, it moves into the **Modeling Layer**, which uses this data to build virtual representations (models) of the physical entities. These models reflect real-time conditions and behaviours, allowing for simulation and analysis (Tuhaise et al., 2023). The accuracy of the models directly depends on the quality of the data received from the previous layer, making this layer deeply interconnected with both the **Data** and **Analysis Layers**.

The **Communication Layer** is responsible for maintaining the data flow between the physical and digital worlds. This layer ensures that data moves from the physical assets to the modelling and analysis systems in real-time, and conversely, enables the digital twin system to send instructions or feedback to the physical assets. Reliable communication is essential for the synchronization of the real and digital environments, making it a critical layer for real-time operations and analysis.

The **Analysis Layer** plays a vital role in processing the collected data and running simulations on the models created in the modelling layer. This layer utilises advanced technologies such as Artificial Intelligence (AI) and Machine Learning (ML) (Haung et al., 2021) to generate insights, predictions, and optimisation suggestions. These insights are vital for making informed decisions about how to optimize or adjust physical operations.

These insights and analysis results are presented to users through the **Application Layer**. This layer serves as the interface between the digital twin system and the end-users, providing them with actionable insights and decision-support tools. Through dashboards, visualizations, and user-friendly applications, this layer ensures that decision-makers can easily access and act on the data and insights generated by the digital twin.

The **Security Layer** is fundamental in ensuring that the entire system remains secure and protected from potential threats. It is responsible for safeguarding data privacy, controlling access to the system, and ensuring the integrity of the platform. The security layer spans across all other layers, ensuring that data transmission, storage, and user access are protected throughout the digital twin's operation.

Finally, the **Feedback and Control Layer** closes the loop by allowing the digital twin system to feed the analysis results and predictions back into the physical system. This layer plays a crucial role in enabling the system to autonomously adjust or optimise physical operations in real time based on the insights generated by the analysis layer.

3.2 Unique domain characteristics of HPP digital twin framework

In the HPP digital twin framework, several unique domain characteristics set it different from general digital twin applications. These distinct features arise due to the specific operational, environmental, and logistical challenges associated with hydropower plants, as shown in Figure 3.

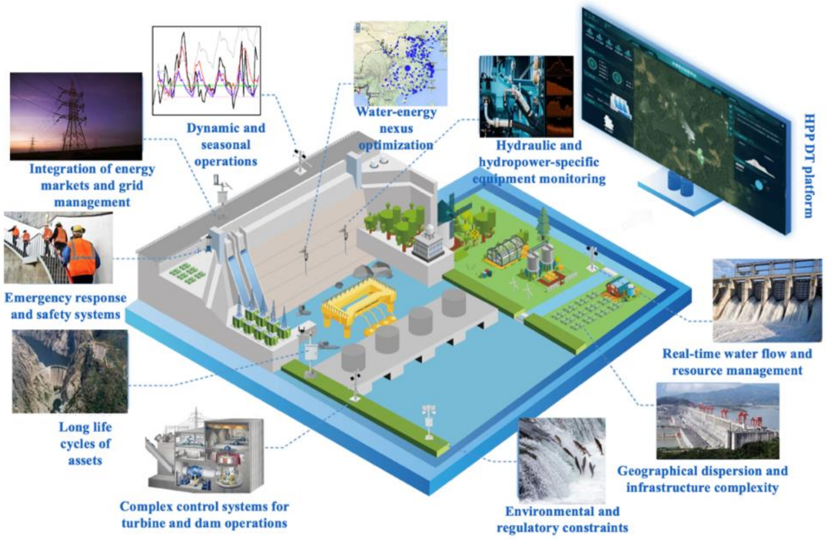

Figure 3. Unique domain characteristics of HPP digital twin framework

Real-time water flow and resource management. HPPs depend on natural water flow for energy generation, meaning the real-time monitoring and prediction of water levels, flow rates, and reservoir conditions are essential. Unlike other DT systems, the variability of natural resources (water availability, seasonal changes, etc.) directly influences HPP operations. The DT must be capable of integrating and forecasting hydrological data to optimise energy production while managing ecological impacts like fish migration and flood risks.

Geographical dispersion and infrastructure complexity. Hydropower plants are often located in remote areas, and the infrastructure (such as dams, turbines, and reservoirs) is typically spread across large geographical regions. The HPP DT must be able to handle geographically dispersed data sources, making it necessary to integrate with IoT and edge computing for real-time remote monitoring. This contrasts with DTs used in more localized or factory-based environments.

Environmental and regulatory constraints. Hydropower operations are subject to strict environmental regulations, particularly concerning water usage, wildlife conservation, and emissions reductions (Khoiyangbam, 2021). The HPP DT needs to incorporate environmental monitoring, compliance reporting, and impact assessments as part of its core functionality, making it more complex than DTs in industries without such stringent environmental constraints.

Complex control systems for turbine and dam operations. HPPs rely on complex control systems to regulate water flow through turbines, manage reservoir levels, and operate gates and spillways (Bernardes et al., 2022). The HPP DT needs to simulate and control these systems in real time, ensuring operational efficiency and safety. The high level of physical system interaction and safety-critical operations are more intense compared to other industries where such real-time, high-stakes control may not be as central.

Long life cycles of assets. Hydropower infrastructure typically has very long operational life cycles, often extending to several decades. The DT must be designed to monitor ageing infrastructure, predict maintenance needs over long periods, and ensure long-term operational efficiency. This requires robust predictive maintenance capabilities to prevent costly downtime or failures, a feature that is not as critical in industries with shorter asset life cycles.

Emergency response and safety systems. HPPs often operate under potentially hazardous conditions, such as dam safety risks (Furtado & Ravena, 2019), flood scenarios (Nguyen-Tien et al., 2018), or mechanical failures. The HPP Digital Twin must integrate sophisticated emergency response simulations and safety protocols to minimize risks. It needs to run scenarios to predict failures in dam infrastructure or turbine breakdowns, ensuring that safety measures are deployed swiftly. This feature is more critical compared to industries with less severe consequences of system failures.

Integration of energy markets and grid management. HPPs often need to balance energy production with demand (Algarvio et al., 2020), particularly in integrated energy markets where hydropower is a key component of renewable energy portfolios. The HPP DT must integrate with energy grids and market platforms to ensure efficient energy dispatch and grid stability.

Dynamic and seasonal operations. The performance of hydropower plants is highly influenced by dynamic, seasonal factors such as rainfall, snowmelt, and droughts (Carpentier et al., 2017), which can vary significantly over time. The HPP DT must have sophisticated predictive capabilities to model these seasonal changes and optimize operations. This differs from DTs in industries with more predictable operating environments, like manufacturing.

Water-energy nexus optimization. Hydropower plants sit at the intersection of water management and energy production, making the efficient use of water critical not just for power generation but also for flood control (Nguyen-Tien et al., 2018), irrigation, and drinking water supplies (Kotulla et al., 2022). The HPP DT must balance these competing demands, optimizing water use for power while ensuring that other water resource needs are met. This adds an additional layer of complexity that general DTs, focused only on energy production, do not need to address.

Hydraulic and hydropower-specific equipment monitoring. HPPs involve specialized equipment such as turbines, penstocks, spillways, and transformers that are unique to hydropower generation (Kumar & Saini, 2022). The Digital Twin must be tailored to monitor, simulate, and predict the performance and maintenance needs of these hydraulic systems and power generation equipment.

3.3 Tailored digital twin framework for HPP

3.3.1 Event-driven architecture

The operational environment of hydropower plants is highly dynamic and complex. Traditional layered architectures, while well-structured, may lack the flexibility and responsiveness needed for real-time operations. The EDDT architecture enhances HPP efficiency by rapidly processing real-time events, such as changes in water flow or system failures, without delays in data transmission. It allows for immediate monitoring and adaptation of operations, optimizing energy output and ensuring system safety. It also promotes modularity and maintainability by reducing dependencies between components, enabling independent updates without affecting system stability.

Specifically, four key reasons for choosing event-driven architecture include **1) Real-time Data Processing and Responsiveness.** Hydropower stations rely on real-time monitoring of parameters like water flow and levels. Event-driven architecture allows rapid responses to changes, automatically adjusting operations for optimal energy output and resource management. It also handles events and alerts from sensors, deploying immediate measures such as adjusting water levels during emergencies. **2) Adaptability to Dynamic Operating Environments.** The hydropower station's operation is influenced by seasonal changes and environmental factors. Event-driven architecture adjusts predictions and operations in real-time, optimizing maintenance and resource strategies. **3) System Decoupling.** This architecture minimizes dependencies between system components, allowing independent updates and maintenance, and enhancing overall reliability and flexibility. **4) Facilitating Innovation and Integration.** It supports integration with other renewable energy sources and systems, enabling innovation in applications such as demand response and market operations.

3.3.2 Operational mechanisms

The implementation of the Event-Driven Architecture (EDA) in the Hydropower Plant Digital Twin framework encompasses several critical components and processes, all working in harmony to ensure efficient, flexible operations and real-time management. The following describes the core elements and their interactions within the updated architecture:

Event Producer: These are the sensors deployed throughout the physical HPP infrastructure. They monitor various physical parameters such as water level, soil moisture, flow rate, rainfall, and environmental conditions like temperature and wind speed. This network of advanced sensors, including flow meters, water level gauges, osmotic pressure sensors, flood monitors, and emergency detection devices, continuously collects real-time data and generates events when predefined thresholds or anomalies are detected. Internet of Things (IoT) devices form the backbone of this network, ensuring continuous data generation and transmission.

Stream Distributor: The Stream Distributor is a central element in the framework, responsible for receiving the raw events generated by the sensors and distributing them to the appropriate consumers (event processors). It functions as a message broker or event bus, facilitating efficient event flow between sensors (event producers) and consumers (event processors). This component ensures that the right data reaches the correct processor based on predefined criteria.

Event Processors (Consumers): Each event processor (consumer) specializes in processing specific types of events. In the updated framework, the key event processors include: 1) **Power Grade Processor**: Monitors power output, optimizing generation based on real-time hydrological data. 2) **Environmental Processor**: Analyzes environmental data (e.g., rainfall, water quality) and ensures regulatory compliance. 3) **Cyber Security Processor**: Identifies and mitigates cyber threats to the HPP infrastructure. 4) **Water Resource Processor**: Balances the water resource needs of the plant with external demands like irrigation and drinking water. 5) **Hydraulic Equipment Processor**: Monitors and ensures the health of turbines, gates, and other critical mechanical components. 6) **Weather Prediction Processor**: Analyzes weather data to forecast conditions that may affect HPP operations. 7) **Market Integration Processor**: Facilitates real-time integration with energy markets to adjust power output based on demand and pricing. 8) **Operational Safety Processor**: Ensures that the system remains in safe operating conditions by monitoring infrastructure risks like dam stability or flood hazards.

These processors leverage processing software and other microservices to classify, filter, and analyze events, ensuring timely and appropriate responses. **1) Decision Support System**: Based on the output from the event processors, this system generates operational commands and suggestions for adjustments, such as regulating sluice gates, adjusting power generation, or initiating emergency response plans. The Decision Support System integrates Artificial Intelligence (AI) and Machine Learning (ML) techniques to optimize decision-making and enhance predictive maintenance capabilities. It communicates its findings and suggestions with both the HPP DT platform and key stakeholders/managers for further decisions. **2) Feedback and Control**: This component executes the operational commands generated by the Decision Support System. Automated control systems adjust physical equipment, such as turbines and sluice gates, based on real-time data and AI-driven insights. This ensures fast, accurate execution of necessary operations and system adjustments, maintaining optimal performance and safety standards.

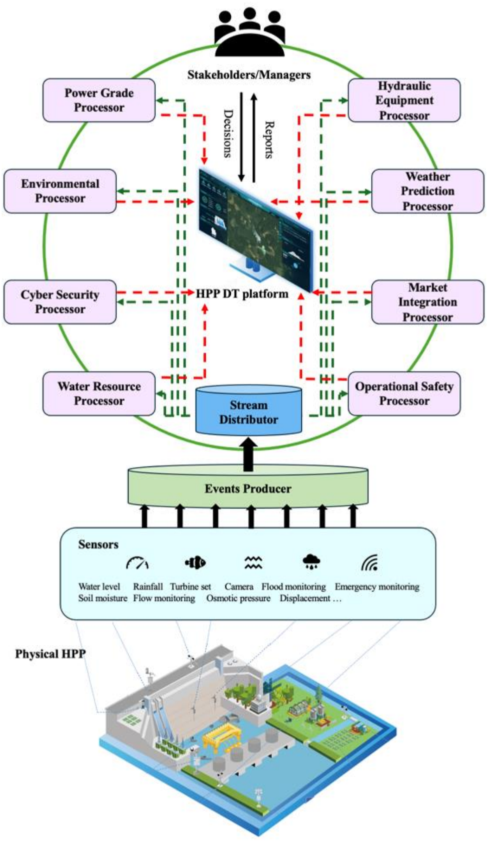

Figure 4. HPP digital twin framework architecture

3.3.3 Core processors

Power Grade Processor. This processor is dedicated to managing and optimizing the power generation aspects of the HPP DT. It processes real-time data concerning hydrological conditions and power output requirements. It evaluates the efficiency of power generation processes, predicts future power supply based on real-time environmental data, and adjusts operational parameters to maximize energy output while ensuring the longevity of physical assets.

Environmental Processor. This processor focuses on processing and responding to environmental data collected from various sensors monitoring weather, water quality, and ecological conditions. This processor uses data to ensure compliance with environmental regulations and to adjust operations to minimize environmental impact. It also predicts potential environmental risks like flooding and adjusts operational strategies accordingly. Utilizes AI-driven models to simulate and predict environmental impacts, incorporating real-time data from IoT devices to facilitate rapid response to environmental changes and alerts.

Cyber Security Processor. It safeguards the integrity and security of the HPP DT system by monitoring, detecting, and responding to cybersecurity threats and vulnerabilities. Manages data security protocols, oversees network security operations, and implements protective measures against potential cyber-attacks and breaches. It also ensures compliance with data protection laws and industry standards. Employs advanced cybersecurity technologies including intrusion detection systems, firewall management, and encryption protocols to protect data transmissions and system operations.

These core processors play a vital role in ensuring the HPP DT system operates efficiently, safely, and sustainably. Each processor is equipped with specific functionalities that address different aspects of the digital twin's operations, from power management to environmental monitoring and cybersecurity, forming a robust foundation that supports the overall integrity and effectiveness of the event-driven architecture.

4. DISCUSSION

4.1 Expected outcomes

The implementation of the EDDT framework for hydropower plants is expected to deliver several key outcomes, improving both operational efficiency and adaptability compare with traditional layer structured DT frameworks: 1) Increased Flexibility: Enables real-time responses to environmental and operational changes, optimizing water management and power generation. 2) Real-Time Responsiveness: Enhance real-time monitoring and control, allowing immediate reactions to key operational events, preventing failures, and optimizing processes. 3) Scalability: Support a growing number of sensors and data inputs without increasing complexity, ensuring robust system growth. 4) Enhanced Predictive Capabilities: Incorporate AI/ML to improve predictive maintenance, reducing downtime and extending equipment lifespan. 5) Better Resource Allocation: Dynamically prioritize resources, ensuring swift responses to high-priority events while efficiently managing routine tasks. 6) Environmental Compliance: Ensure adherence to environmental standards through real-time monitoring of water management and conservation. 7) Improved Safety: Enhance safety through real-time monitoring of potential hazards, enabling faster response to emergencies such as dam safety or equipment failure. In summary, the EDDT framework will boost the efficiency, sustainability, safety, and scalability of hydropower plant operations.

4.2 Potential Challenges

While the EDDT framework offers significant benefits, it also presents challenges in complex hydropower environments: 1) Increased System Complexity: Managing asynchronous event flows, ensuring consistency, and avoiding duplication or loss becomes harder as the system scales. This requires advanced event routing, logging, and monitoring to maintain integrity. 2) Event Overload: High-frequency events, such as sudden weather changes, can overwhelm the system. Effective filtering and prioritization, including complex event processing (CEP), are necessary to prevent delays in handling critical issues. 3) Difficult Debugging and Tracing: Debugging in event-driven systems is more complex than in traditional layered architectures due to concurrent and independent event processing. Advanced logging and monitoring tools are needed to trace and resolve issues, increasing maintenance demands.

4.3 Case scenarios

The proposed EDDT framework will be tested and applied in the Kremasta and Ilarion Hydropower Plants in Greece. The Kremasta HPP is the largest Hellenic hydroelectric power plant. It is located on Acheloos river/basin in West Continental Greece, and it is used for hydropower production and flood control. It is an earth fill power plant with total installed capacity 437 MW produced by four Francis turbines with a nominal power of 109 MW each. The HPP’s mean annual production is 848 GWH and the height of waterfall is 132 m. And the Ilarion is a relatively new (operated commercially for the first time in 2014) hydro power plant located on Aliakmon River in Western Macedonia. It is used for hydropower production, irrigation and water supply and it has a total installed capacity 153 MW that is produced by two Francis turbines with a nominal power of 76 MW each. The HPP’s mean annual production is 320 GWH and the height of waterfall is 104 m.

5. CONCLUSIONS

This study proposed an EDDT framework specifically tailored for hydropower plants, aiming to enhance operational flexibility and responsiveness. The framework effectively leverages event-driven architecture to allow real-time system adjustments in response to environmental and operational changes.

This adaptation is crucial for managing the dynamic and complex nature of water resources inherent in hydropower systems. While the EDDT framework promises significant improvements in efficiency and sustainability, its implementation is challenging due to the increased complexity and management demands. Future research should focus on refining the integration and operational processes to mitigate these challenges. As part of the D-HYDROFLEX project, the proposed EDDT framework will be tested and applied in real-world conditions, specifically in operational the Kremasta and Ilarion Hydropower Plants in Greece (D-HYDROFLEX, 2024). This will allow us to validate the expected outcomes and address potential challenges in a practical setting, contributing valuable insights to future digital twin implementations in the hydropower sector. Overall, the proposed digital twin framework sets a foundational approach for future advancements in the digital management of renewable energy systems.

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