Digital Twins for Operation and Monitoring of Inland Waterways and Infrastructure

TERMS OF REFERENCE

1. Historical Background & Problem Definition

The developement and use of digital twin models are becoming a common practice for the design and exploitation of waterborne infratructures. Even if the range of applications is wide and includes ports and maritime transport, the WG 257 is focussing on inland waterways and IW infrastructures. In the future, PIANC may launch further Working Groups looking at the use of digital twin models in ports, coastal and offshore applications.

IW structures—such as canals, locks, aqueducts, dams, and weirs—are inherently complex due to their mechanical, thermal, and hydraulic interactions with water, which makes traditional modeling difficult. These structures are built from a variety of materials and can have different foundation types. Aging infrastructure often lacks documentation of past repairs, leading to uncertainties about construction methods. Many structures are centuries old and include hard-to-reach areas, complicating monitoring efforts. Additionally, the governance and management of this infrastructure by multiple organizations further adds to operational challenges.

Considering the complexities of IW and its infrastructure, operating and monitoring hydraulic navigation structures presents significant challenges, particularly when managing and analyzing the vast quantities of data ("big data") these systems generate.

Digital twin technologies, often powered by machine learning algorithms, offer promising solutions to these challenges. To effectively implement digital twins in inland waterway management, several challenges must be addressed:

- To establish an universal definition for digital twins of hydraulic and navigation structures.
- Identify existing applications to establish foundational knowledge and best practices, while developing interoperability standards which will enhance integration capabilities for operating and monitoring inland waterways and their infrastructure.

2. What is a "Digital Twin" Model?

A Digital Twin model is a digital replica of a real object (such as a structure) or process (such as river flow) or system (interaction between river flow and structure).

A Digital Twin system may be defined as follows (ISO/IEC 30173:2023 "Digital twin – Concepts and terminology"):

A Digital Twin (DTw) is a digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization. It has some or all of the capabilities of connection, integration, analysis, simulation, visualization, optimization, collaboration, etc. It can provide an integrated view throughout the life cycle of the target entity.

The concepts of digital model, digital shadow and digital twin are associated but they differ each another:

- A digital model is a static representation of a physical object or system that captures its design or structure without incorporating real-time data flows.
- A digital shadow reflects real-time data generated from the physical object's operations, creating a passive data flow that shows the current state of the system.
- A digital twin, by contrast, actively utilizes this data flow, integrating real-time information to simulate, analyze, and optimize the physical system's performance.

Digital twins have experienced significant growth in recent decades, driven by advances in artificial intelligence, big data, and the Internet of Things. These digital representations can track an object throughout its life-cycle, understand its behavior at varying levels of sophistication, and simulate its characteristics.

Behind this fascinating and attractive general concept, several sophisticated techniques may be hidden to make the use of digital twins' models user friendly without necessarily relying on heavy modeling. Often the objective is to provide real-time results and forecasts in the simplest and fastest manner possible.

The underlying complexity of digital twins, even when well-designed and calibrated, requires careful consideration to avoid "black box" effects where users may not fully understand the system's decision-making processes. These considerations necessitate a collaborative effort through a PIANC Working Group to thoroughly examine digital twin technology, including its advantages and limitations.

3. Objectives of the WG

The WG 257 has the following objectives:

- Develop a common definition for Digital Twins of hydraulic and navigation structures that includes specific maturity levels.
- Develop a definition of maturity levels, which can help to effectively communicate goals, expectations and limitations more reliably.
- Consolidate initial experiences and feedback's from digital twin applications in hydraulic and navigation structures through case studies.
- Identify potential new applications of digital twins to facilitate or improve the operation and monitoring of hydraulic navigation structures.
- Establish baseline standards for digital twin interoperability, especially where digital twins are applied for construction and monitoring of physical structures.

4. Examples of Digital Twins for IW

Few examples of practical uses of digital twins are:

- Digital Twin of Fairway (NL) was developed through a collaboration between Deltares, Delft University, SmartPort, MARIN, Port of Rotterdam, Port of Amsterdam, Danser, NPRC, Koninklijke Binnenvaart Nederland and Rijkswaterstaat and aims to become a platform to test out and exchange data, tools and models.
- Digital Twin of Embankment and Concrete Dams (USA), has as objective to develop and implement a digital twin framework for two dams in the United States: An embankment dam and a concrete dam.

- Digital twin of the navigable waters paving the way for e-navigation (IHO project), *https://iho.int/en/the-digital-twin-of-the-navigable-waters-paving-the-way-for-e-navigation*.
- Monitoring of dams or dikes (ISL-Fr): The digital twin has been tested on various types of monitoring measurements: displacements (pendulums, inclinometers, extensometers), pressure (piezometers), temperatures, and leakage rates. The technology can be extended to storm surge barriers, navigation control weirs, side walls of locks, gates of locks and weirs, sheet piles, etc.
- French ISL's "flash flood" digital twin was designed to protect a construction site from flash floods, typically caused by heavy rainfall over a short period (as Valence, Spain in Nov 2024).
- Monitoring and Sustainability of the Douro: Digital Twin is a critical tool for managing the interdependencies between navigation, hydroelectric power, and environmental sustainability along the Douro Waterway.
- Digital twins Large Language Models hold significant potential to bridge technical gaps and enable increased explainability and bespoke data analysis for Digital Twins. This is an emerging area of research.
- DTw for Multipurpose use of the Plassendale-Nieuwport Canal (BE): A support instrument to allow stakeholders effective management of navigation, droughts, floods and salt intrusion

These case studies (and others) will be developed in the WG 257 report.

5. Earlier reports to be reviewed

Not Applicable (N/A)

6. Scope of work

The Working Group will address the following:

1. **Current State Assessment**
   Review and define the state of the art in digital twin applications for inland waterway and waterborne infrastructure.
2. **Requirements Analysis**
   Develop a comprehensive inventory of digital twin requirements for IW hydraulic and navigation infrastructure, with particular attention to:
   - Continuous monitoring needs for dynamic management
   - Topo-bathymetric data collection
   - Hydraulic data measurement
   - Dynamic Adaptive river management strategies based on:
     - Monitored status,
     - Operational feedback,
     - Forecasted environmental condition.
3. **Technical Review**
   Inventory, review and assess the current digital twin technologies, including the use of conceptual modeling, artificial intelligence, machine learning and large language models, augmented reality (AR), virtual reality (VR) and other emerging approaches.

4. **Case Studies**

Compile and analyze lessons learned from existing digital twin implementations.

5. **Future Applications**

Evaluate potential future uses of digital twins, including, benefits and opportunities, implementation challenges, technical barriers and solutions.

Consider the risk associated to the long life time of waterborne infrastructures (typically 100 years) and the maintenance of digital twins models based on data stored on hardware which are typically outdated after 5 or 10 years.

6. **Implementation Standards**

These baselines (to be completed) relate for instance to: Simulation and Modeling standards, Time synchronization, Establish baseline standards for digital twin design, operation, and integration, addressing:

- Validation methodologies,
- Data format standardization,
- Simulation and modeling protocols,
- Time synchronization requirements,
- Integration specifications.

7. Intended product

The WG will produce a written report, including case studies and recommendations for the implementation of Digital Twins for the design, construction, operation, monitoring and maintenance of IW infrastructure.

8. Working Group membership

The WG aims to include membership from the following groups:

- Academic and Research Communities: IW specialists, civil engineering researchers and related scientific disciplines;
- Engineering Organizations: Firms with digital twin development experience, organizations planning digital twin implementations, and model calibration specialists;
- Public Administration: Port authorities, IW administrators, digital twin system users;
- Industry Professionals: Technical consultants and software developers;
- Contractors.

9. Target Audience

The report will serve IW managers, port administrators and engineering firms interested in developing and implementing digital twin models for infrastructure design, operation, and maintenance.

10. Relevance

10.1. Relevance to countries in transition

Digital Twins technology may drastically ease Inspection and Maintenance (I&M) efficiency and effectiveness, particularly in countries of transition where funds are lacking for I&M.

10.2. Climate Change and Adaptation

Digital Twins can provide insights on the potential impact of climate change and pathways for adaptation. Special focus will be placed digital twins for real-time river flow forecasting, particularly in the context of climate change. Identifying socio-economic and environmental data needs will be relevant for improving the usefulness of digital twins for adaptive management of inland waterways.

10.3. Working with Nature

Digital Twins support Working with Nature principles through real-time river flow monitoring, support for integrated environmental analysis and predictive model capabilities.

10.4. UN Sustainable Development Goals

This working group's objectives align with several UN Sustainable Development Goals, including improving infrastructure management and environmental monitoring, sustainable resource utilization and climate adaptation support.

11. References

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