Digital Twin Case Study 1: Digital Twin Fairway

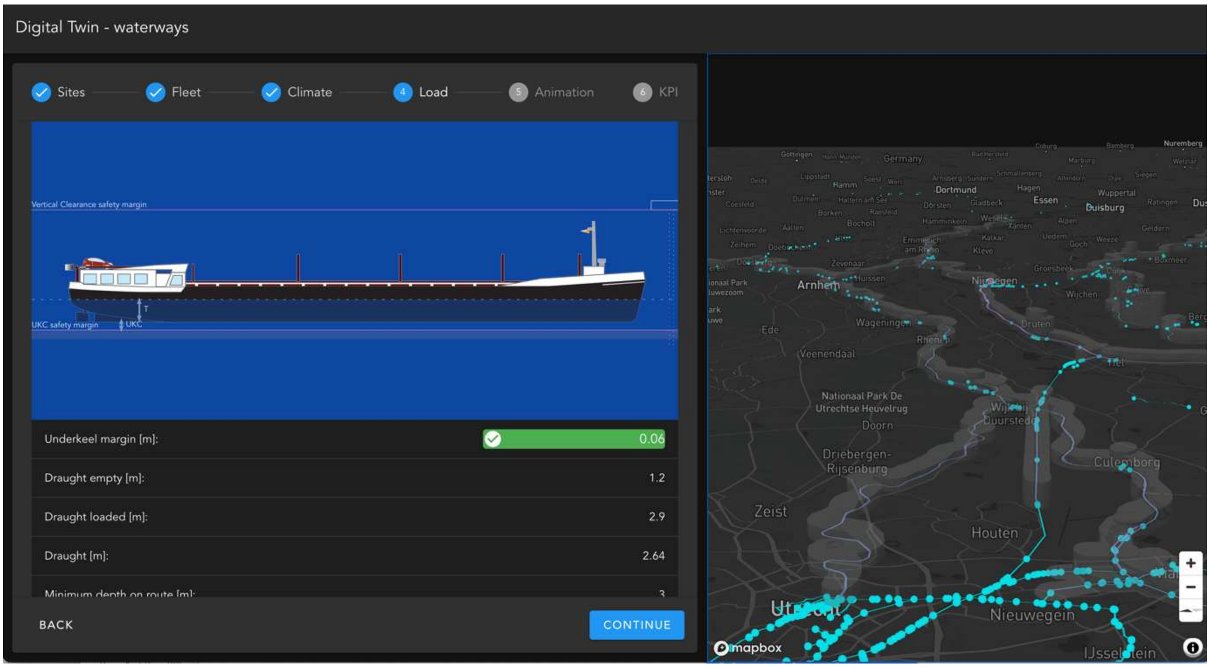
SHORT DESCRIPTION

The Digital Twin Fairway is intended to cooperate on the following objectives:

- **Scenario Analysis**: The digital twin allows barge operators and infrastructure managers to assess the implications of various future scenarios. This includes evaluating fleet utilization and waterway capacity.
- **Sustainability and Climate Resilience:** Amid the energy transition and climate change, the inland shipping sector faces challenges. The digital twin helps make informed decisions regarding sustainable investments and adaptability to extreme river water levels.
- **Collaboration:** Developed through a collaboration between Deltares, Delft University, SmartPort, MARIN, Port of Rotterdam, Port of Amsterdam, Danser, NPRC, Koninklijke Binnenvaart Nederland and Rijkswaterstaat the Digital Twin aims to become a platform to test out and exchange data, tools and models.

This digital twin focuses on inland waterways, particularly between Rotterdam and Basel. Based on the EURIS initiative, it is being extended to the entire European waterways. A number of datasets and tools are incorporated as components, some main components include:

- Topological Network of the Dutch Fairway Information System [4], a graph network for routing and exchanging geospatial and physical information
- OpenTNSim [5]: Discrete Event Simulation with support for fairway use, includes energy, emissions, capacity as a function of waterdepth [6], locks, berthing and other fairway related concepts.
- SOBEK emulator: **surrogate version** of SOBEK hydrodynamic model, used for interactive climate impact (water depth and currents as a function of discharge) computations.



The domain is limited to the spatial extent of the Dutch Fairway Information System (NL, BE, DE). Tests are conducted with a topological network based on EURIS (EU). The temporal domain is typically weeks through years..

SPECIFITIES OF THE DTw :

When we compare the definition of traditional digital twins with a focus on lifecycle management of singular objects, this digital twin is different in several ways:

- Two-way data flow: Some consider this a precondition for a digital twin. But in the environmental world this is a less common property. In the problem domain of this digital twin (spatial planning, fairway design, maintenance prioritization, testing transport concepts) there is less interest in having real time updates from the system. As there is more focus on scenarios than real time updates.
- 3D visualization. Although the system uses a 3D visualization engine (mapbox-gl) it uses a tilted flat, high tech styled view of the earth. The users preferred this to 3D visualizations of the ships and ports. Both visual aspects (less clutter) and the costs of 3D visualizations played a role in choosing for this bird eye view over a 3D view.
- Users also have access to the underlying data and models using REST API's and example notebooks. Engineers often skip the Digital Twin interface or only use it to setup an example scenario, and use a notebook interface to automate their workflow. The interface in it's current form is mainly used for demonstration and education.

References :

[1] Digital Twin voor grip op binnenvaartlogistiek: https://smartport.nl/digital-twin-voor-grip-op-binnenvaartlogistiek/.

[2] Digital Twin Fairway Corridor – SmartPort: https://smartport.nl/project/digital-twin-fairway-corridor/.

[3] TRANS2: https://publicwiki.deltares.nl/display/TKIP/DEL170+-+TRANS2%3A+TRANSitie+naar+een+klimaatbestendig+en+duurzaam+Rotterdams+achterlandTRANSport

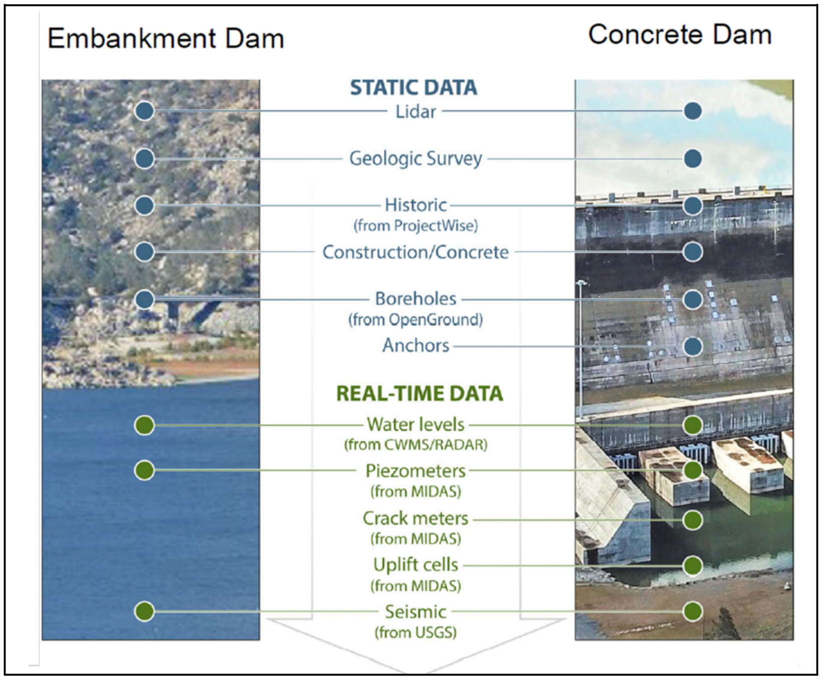
[4] https://zenodo.org/records/6673604

[5] https://github.com/TUDelft-CITG/OpenTNSim

[6] https://journals.open.tudelft.nl/ejtir/article/view/3981

Digital Twin Case Study 2: Embankment and Concrete Dams

SHORT DESCRIPTION: The objective of this effort was to develop and implement a digital twin framework for two dams in the United States—an embankment dam and a concrete dam. The framework was designed to ensure adaptability through modular design, flexibility by being platform-agnostic, and seamless integration with existing technologies, infrastructure, and databases. By consolidating silo-ed authoritative data sources, the digital twin enabled data and workflow automation, providing a comprehensive view that supports more efficient decision-making.



SPECIFICITIES OF THE DTw: The effort was driven by 9 specific questions developed by the stakeholders on the condition of the dam, related to specific measurements, conditions, and ratings. The ability to answer these specific questions drove the scope of the project. Ultimately, the impact of the model was to leverage real-time and near real-time information to predict the asset condition, and better inform the safety and investment decisions. The effort was broken into 5 primary focus areas, including (1) user interface and visualization, (2) sensing stream management, (3) data reduction and synthesis, (4) risk modeling, and (5) data analytics with threshold and decision statistics. For this particular effort, the digital twin maturity spectrum was defined as:

1. Model of the physical asset
2. Model connected to static data
3. Model connected to real-time data
4. Model-and-human two-way communication
5. Digital Twin with real-time feedback

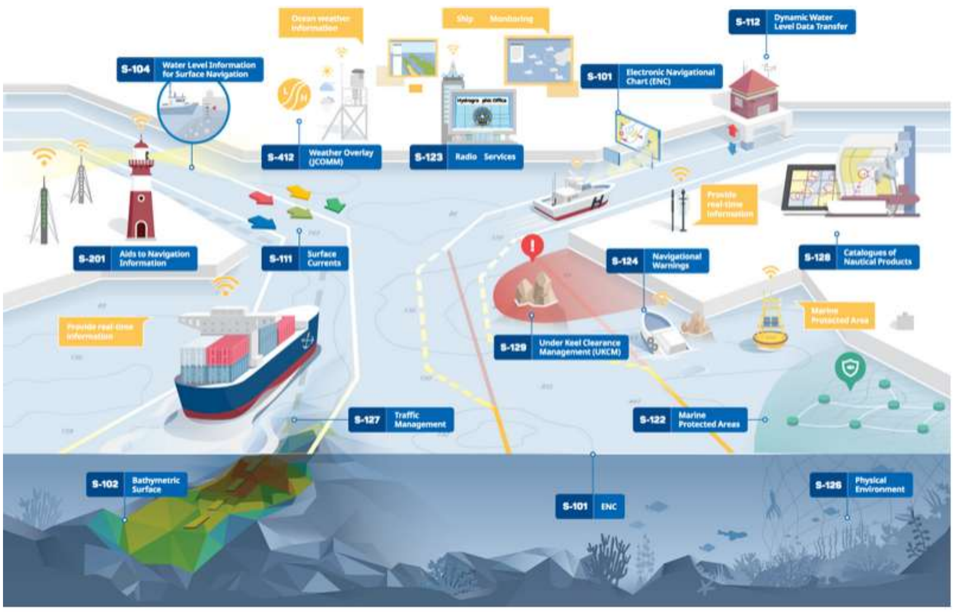
Digital Twin Case Study 3: Digital Twin of Navigable Waters

SHORT DESCRIPTION:

The **Digital Twin of Navigable Waters** is an innovative project by the **International Hydrographic Organization (IHO)** aimed at advancing maritime navigation and autonomous shipping. This digital twin creates a synchronized virtual model of navigable waters, allowing for real-time data exchange between the physical environment and its digital counterpart. By supporting both the monitoring and control of real-world conditions via its digital interface, it enhances safety, efficiency, and decision-making in maritime operations. The initiative is built on the IHO's **S-100 Universal Hydrographic Data Model**, which integrates diverse and standardized maritime data.

SPECIFITIES OF THE DTw:

- The Digital Twin continuously synchronizes real-world data, enabling real-time monitoring, analysis, and control of navigation and environmental conditions.
- At the core of this project is the IHO’s S-100 data model, which defines data product specifications to ensure seamless integration and interoperability of maritime data.
- The IHO is on track to operationalize several S-100 compliant data products by the end of 2024, with a focus on key areas like route tracking. Additionally, several IHO Member States have committed to providing regular data services to the shipping industry by 2026.
- By 2029, all new ECDIS (Electronic Chart Display and Information Systems) will be required to support and display S-100 products and services. This second phase will expand to cover more thematic areas and maritime services, further enhancing digital navigation capabilities.
- Test beds were established in 2022 in regions such as the North Sea and Baltic Sea to evaluate the Digital Twin’s functionality in real-world maritime conditions.



Within the S-100 framework, data from different disciplines can be used together in the same system. ©KHOA

Reference: International Hydrographic Organization (2024): “The digital twin of the navigable waters: paving the way for e-navigation”, https://iho.int/en/the-digital-twin-of-the-navigable-waters-paving-the-way-for-e-navigation

Digital Twin Case Study 4: Flash flood forecasting

SHORT DESCRIPTION

Flash floods are sudden and rapid floods, typically caused by heavy rainfall over a short period. Unlike slower floods that result from the gradual rise of rivers, flash floods occur quickly, sometimes within minutes or hours after the rain. These floods can cause a serious danger due to their strength and speed, causing material damage and posing risks to human life.
The "flash flood" digital twin was initially designed to protect a construction site from flash floods. However, it can be extended to many other applications. It is currently in an advanced stage of development before its deployment.

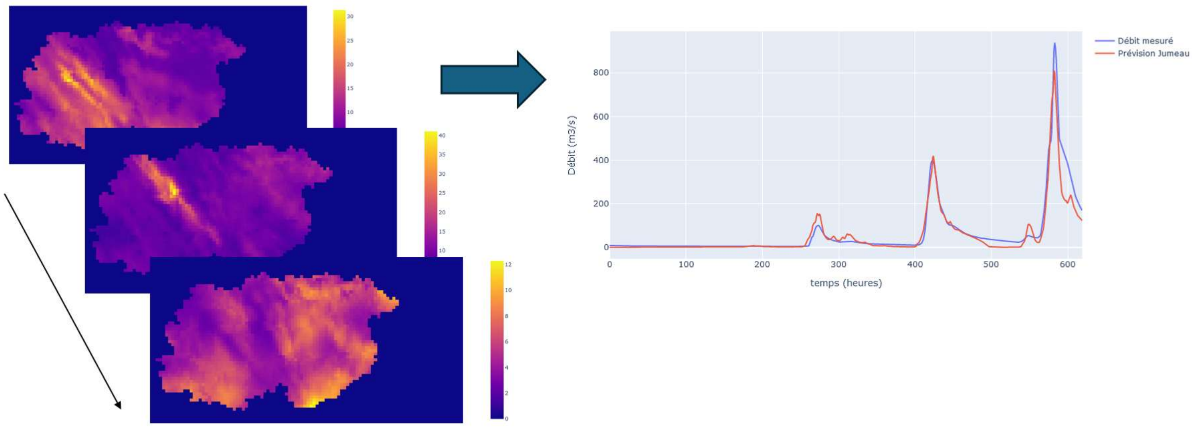
SPECIFITIES OF THE DTw :

The digital twin takes as input radar rainfall images. These images can be provided in real time or from a weather forecast. The digital twin immediately computes the corresponding flood at a given point.

The digital twin combines Deep Learning techniques with a conceptual model of hydrology and hydraulics. The integration of upstream hydraulic structure management is currently under development and will allow for potential optimizations of this management.

Calibration of digital twin can be done with some historical data, and then continued in real time to be improved.

Examples of a case study in France: this example is a real forecast and not the result of calibration process. The digital twin has been calibrated on previous historical floods.



<u>Digital Twin Case Study 5:</u> Smart Monitoring Twin

SHORT DESCRIPTION

Nowadays, the analysis of monitoring data is mainly conducted using statistical methods (such as the well-known *Hydrostatic-Season-Time* method- HST). These methods are used for their simplicity and portability. However, the downside is that they do not capture the complexity of the physical reality they represent. They merely follow trends, which can often lead to misjudgments when the monitored structure is subjected to loads or combinations of loads which never occurred before. This is particularly true for hydraulic structures, which can be exposed to highly variable loads: internal/external or upstream/downstream hydraulic pressures, temperatures, embankment thrusts, concrete swelling, etc.

On the other hand, the use of complex methods, such as finite element modeling, does not provide an ideal solution either. These methods cannot fully capture the complexity of the monitored reality (for example, water seepage through a dike), require specific knowledge and software's, and often involve a lengthy development process that is incompatible with the need for quick decision-making.

In this context, ISL (France) has initiated an ambitious research project to leverage digital twins in the monitoring of hydraulic structures. **The idea is to develop an intelligent twin that understands the physics of the monitored structure and automatically adjusts itself to determine whether the observed behavior is acceptable or not**.

To achieve this, the digital twin combines two approaches:

- A machine learning-based approach,
- A physics-based approach: several techniques are proposed to help the twin understand the expected physical behavior detected by the sensors.

This approach is customizable, allowing the twin to be more weighted toward one approach or the other. It can therefore track and represent both physical effects known with a certain level of accuracy, as well as empirical effects, which are real but difficult to capture precisely (such as local masonry damage or localized seepage through root systems).

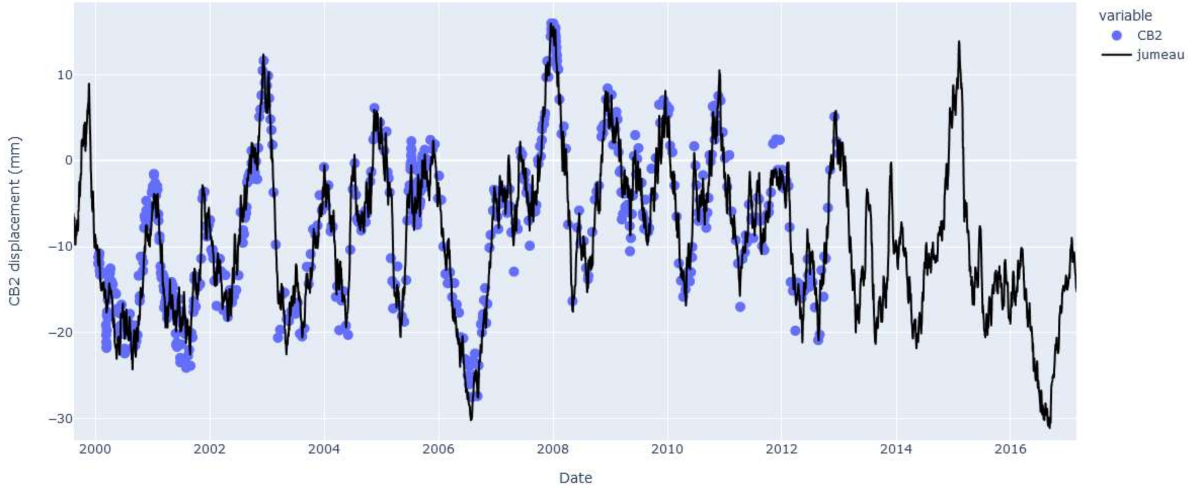
The digital twin has been tested on various types of monitoring measurements, such as displacements (pendulums, inclinometers, extensometers), pressure (piezometers), temperatures, and leakage rates.

The results are promising as the twin provides more precise and richer predictions than statistical methods, particularly for loads that the structures have never experienced before.

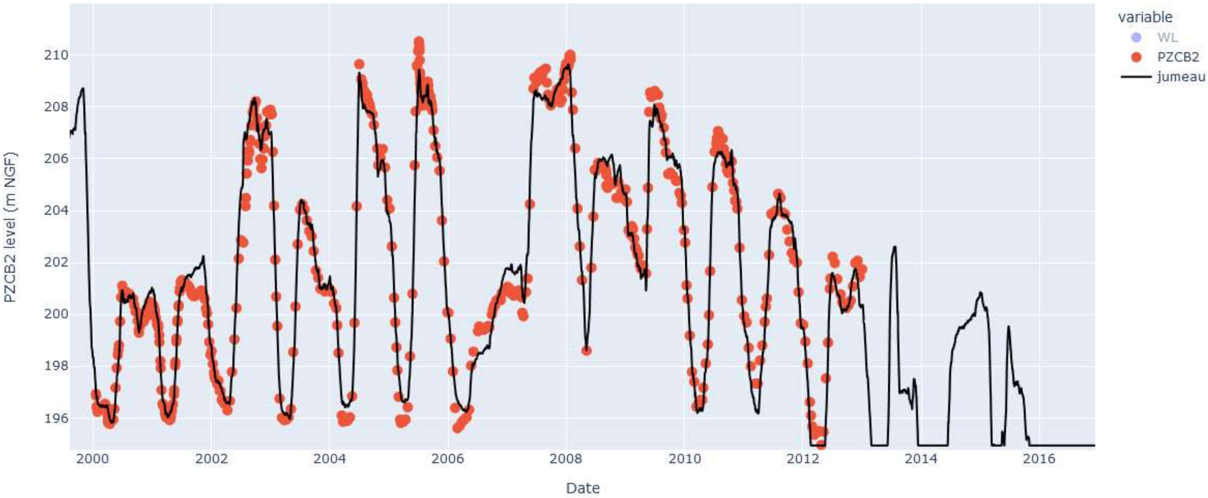
SPECIFITIES OF THE DTw :

Examples of digital twin results:

- **Pendulum (displacement) monitoring**



- **Piezometer monitoring**



Digital Twin Case Study 6:

Monitoring and Sustainability of the Douro Inland Waterway

The Digital Twin for the Douro Waterway was designed to enable interconnected and real-time monitoring, simulation, and decision-making across the waterway's operational and environmental domains. The application integrates digital twins of key components, including the waterway, hydroelectric power plants (with real-time discharge flows linked to energy production requirements), and erosion models to assess the impact of vessel speeds on bank stability. The system provides a dynamic and holistic view to support sustainable, efficient, and safe waterway management.

SPECIFITIES OF THE DTw :

- **Integrated Digital Twins**: Includes models of the waterway, hydroelectric power stations (discharge flows linked to energy needs), and bank erosion to provide a complete, real-time overview of operational and environmental conditions.
- **Real-Time Data Processing:** Uses streaming technology for continuous data input from sensors and systems, enabling timely monitoring and response.
- **Decision Support and Visualization**: Provides interactive dashboards for real-time data visualization and scenario simulation to assist in navigation scheduling, speed adjustments, and discharge coordination.
- **Interoperability**: Designed for compliance with standards like S-100, ensuring smooth integration with other maritime and environmental systems.

Use Scenario: During peak energy demand, the hydroelectric stations increase production, resulting in elevated discharge flows. The Digital Twin system, integrating real-time data, predicts the impact on downstream water levels and currents. Erosion models identify increased erosion risks. The system recommends adjustments to vessel schedules, speeds, and lock operations to maintain safety and reduce environmental impact, while keeping stakeholders informed for effective decision-making.

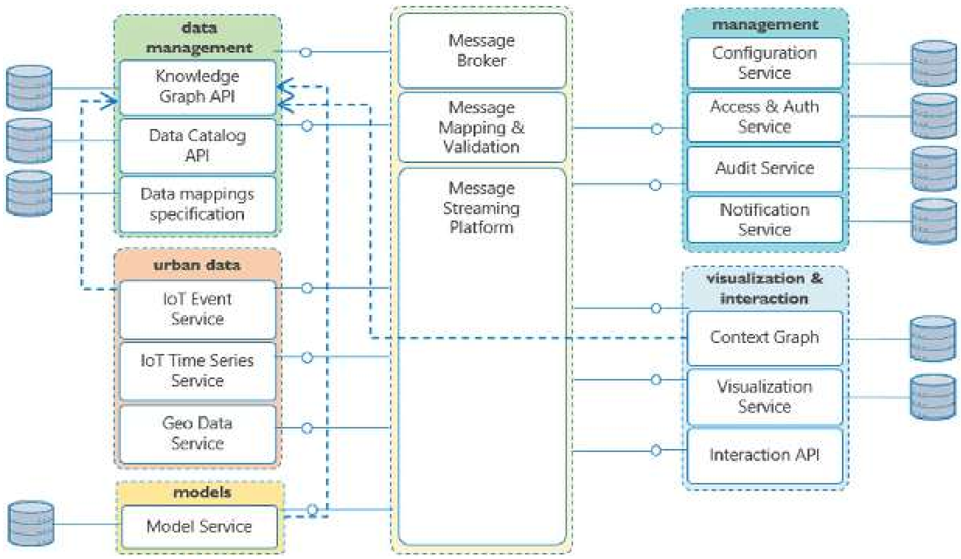


Figure 1 - DUET T-Cell Douro System, with modules containing decoupled services

This Digital Twin application is envisioned as a critical tool for managing the interdependencies between navigation, hydroelectric power, and environmental sustainability along the Douro Waterway.

References:

[1] DUET T-Cell Architecture for Interoperability | https://www.digitalurbantwins.com/technical-approach

[2] DUET: A Framework for Building Secure and Trusted Digital Twins of Smart Cities | Lieven Raes, Philippe Michiels, Thomas Adolphi, Chris Tampère, Athanasios Dalianis, Susie Mcaleer, Pavel Kogut | https://www.researchgate.net/publication/349602444_DUET_A_Framework_for_Building_Secure_and_Trusted_Digital_Twins_of_Smart_Cities

Digital Twin Case Study 7:

Large Language Models for Explainable Decisions and Bespoke Data Analysis in Dynamic Digital Twins

Digital twins (DTWs) are powerful tools for complex decision-making, but their complexity can create a "black box" effect, hindering trust and adoption. This is particularly true in dynamic environments where real-time insights are crucial. Integrating Large Language Models (LLMs) offers a dual solution: enhancing explainability *and* enabling bespoke data analysis on demand. LLMs not only translate complex outputs into understandable narratives but also empower users to query DTW data directly using natural language, fostering transparency and deeper understanding of the underlying model. This case study explores how LLMs achieve these objectives and contribute to more effective human-AI collaboration in the context of inland waterways and ports.

Integrating LLMs within DTWs unlocks several key capabilities:

Enhanced Explainability: LLMs translate complex data, model outputs, and decision rationale into natural language, fostering trust and allowing validation of the DTW's processes

On-Demand Bespoke Data Analysis: LLMs empower users to perform ad-hoc data analysis by querying the DTW directly using natural language. This eliminates the need for specialized programming skills and allows non-technical stakeholders to explore data and gain personalized insights.

Improved Data Transparency: By providing easy access to data explanations and supporting bespoke analysis, LLMs enhance transparency and reveal the underlying relationships within the DTW model.

Real-Time Decision Support: LLMs provide real-time explanations and analysis of dynamic DTW outputs, aiding informed decisions in rapidly changing situations like incident management.

Enhanced Human-AI Collaboration: Natural language interfaces powered by LLMs create a more intuitive and collaborative interaction between humans and DTWs, promoting deeper understanding and trust.

Example Applications:

Predictive Maintenance:"Why does the DTW predict this pump will fail?" The LLM can provide a detailed explanation, including sensor readings, historical trends, and the underlying predictive model's logic. A user could then ask follow-up questions, such as, "Show me historical failure rates for similar pumps."

Traffic Management:"What is the optimal vessel routing given current conditions?" The LLM can explain the DTW's routing suggestion and then provide on-demand analysis like, "Compare estimated arrival times for alternative routes considering predicted tides."

Environmental Monitoring: "What are the main contributors to poor water quality in this area?" The LLM can explain the DTW's assessment and provide further analysis, such as historical pollution trends or the impact of specific industrial activities.

Digital Twin Case Study 8:

DTw Multipurpose use of the Plassendale-Nieuwport Canal

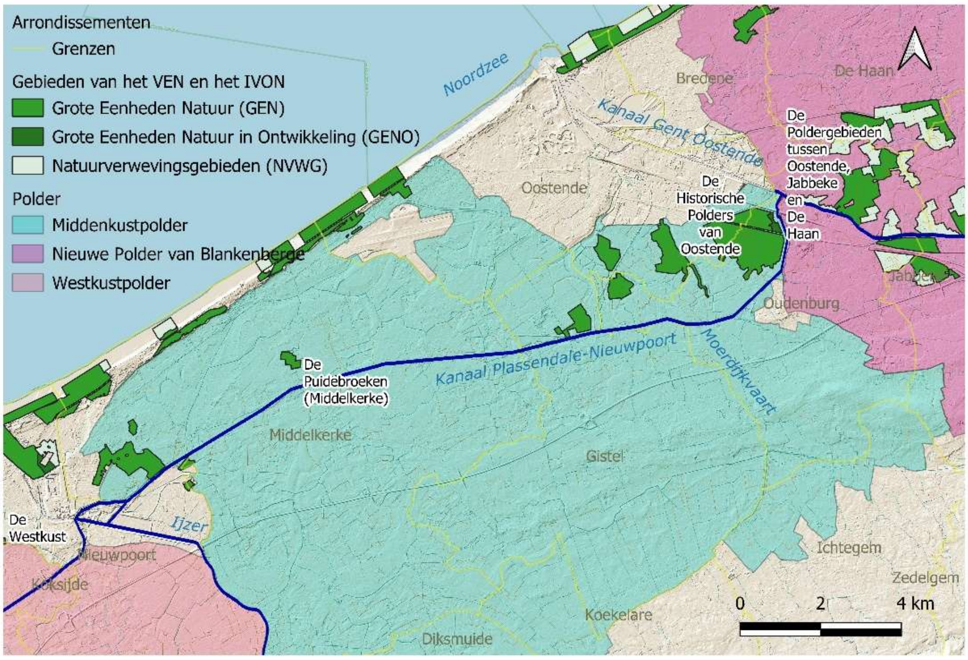
SHORT DESCRIPTION (Objectives of the Digital Twin, Domain, …):

The Plassendale-Nieuwpoort Canal (KPN) serves as a vital link between the water systems of the Yser Basin and the Scheldt River (via the Gent-Oostende Canal, KGO), traversing a large poldered area that includes significant agricultural and urban zones. Additionally, it acts as a crucial hinterland connection between the coastal ports of Ostend and Nieuwpoort.

The canal primarily receives water from the Leie, the KGO, the polders, and to a lesser extent, the Yser. It also interacts with nearby polders such as the Nieuwe Polder van Blankerberge in the northeast, the Westkustpolder in the west, and the Zuidijzerpolder in the southwest.

Various stakeholders have expressed interest in exploring the canal's potential for a range of alternative uses, including flood and drought management, combating saltwater intrusion, and increasing shipping capacity. They also aim to promote tourist shipping, while ensuring that water level management benefits the local ecology and optimizes secondary functions of the canal, such as recreation, ecology, and economy.

To address these challenges, a digital twin of the Plassendale-Nieuwpoort Canal is being developed (KPNtwin). This tool will enable responsible authorities and stakeholders to engage in productive dialogue, identify and assess feasible multi-use scenarios, monitor canal performance, and support operational management and decision-making.



SPECIFITIES of the Plassendale-Nieuwpoort Canal DTw :

KPNtwin is powered by miraX, a cloud-based platform and application specifically designed for creating digital twins of water systems (https://mirax.haedes.eu/). The system's architecture comprises a robust set of customized "adaptors" that establish real-time connections with various data sources, such as geospatial data and time series. These adaptors integrate seamlessly with operational models, feeding data into the internal processing engine, which then drives a modern user interface. Key components of the system include:

- Geospatial Data Integration: This involves the integration of geospatial data from various sources, such as satellite imagery (e.g., Sentinel, Copernicus, ESA, JAXA, NASA), aerial photography, Geographic Information Systems (GIS), remote sensing technologies, and GPS systems. The data includes multispectral images, topographic maps, land use patterns, elevation models, hydrological features (such as rivers, canals, and floodplains), and infrastructure layouts (e.g., roads, bridges, pumps, and locks).
- Continuous Data Integration: This ensures the seamless flow of real-time data from diverse sources, including data providers, sensors, and IoT devices embedded within the water system. It enables the continuous monitoring of key parameters like water quality, flow rates, pressure, and other critical variables, providing up-to-date information for effective system management. A key aspect of this integration is the incorporation of external forecast products (such as Waterinfo, ECMWF, Copernicus, and EFAS), offering valuable insights into future conditions.
- Predictive Modeling: The platform integrates sophisticated algorithms, including water balance and allocation models, alongside machine learning techniques, to simulate future scenarios, predict potential issues, and evaluate the impact of different management strategies. This enables proactive decision-making and optimization of water system operations.
- Interactive Dashboards: The system features interactive dashboards that present real-time data and simulation outcomes in an intuitive, visual format. These dashboards support quick and informed decision-making by providing users with a clear overview of the system's status.
- 2D/3D Geographic Visualization: The system provides immersive 2D and 3D visualizations of the water infrastructure, facilitating a deeper understanding of the system's layout and condition. This tool is particularly useful for planning maintenance activities, assessing system performance, and identifying areas that require attention.