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Digital twins for zero-emission inland waterway transport

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Developing digital twins for zero-emission and climate-resilient inland waterway transport

Inland waterway transport (IWT) is one of Europe's most energy-efficient freight modes, requiring far less energy per tonne-kilometre than road or rail. Yet, it still contributes to greenhouse gas emissions. Under the European Union (EU) commitment to climate neutrality by 2050, transitioning IWT to zero-emission (ZE) operation has become a key but complex systemic challenge. IWT system performance is shaped by fluctuating water levels, which affect navigability, vessel loading capacity, and energy consumption, as well as by infrastructure constraints and an ageing, heterogeneous fleet.

Addressing these challenges requires an integrated approach linking multiple systems, domains, and spatial and temporal scales. A digital twin can provide such a framework by integrating logistics, infrastructure constraints, environmental conditions, fleet composition, operational dynamics, and energy systems. This enables stakeholders to assess operational, tactical, and strategic decisions within a consistent digital environment.

In the short term, it can support operational optimisation and retrofit or fuel-switch strategies. Over the longer term, it can enable coordinated logistics optimisation, infrastructure planning, resilience analysis, and fleet transition modelling to support the ZE transition of IWT while strengthening climate resilience.

Digital twins for IWT

A digital twin is a virtual representation of a physical object or system whose state evolves over time through the integration of models and data.⁽¹⁾ In the IWT context, a digital twin combines core elements that realistically characterise IWT systems, bidirectional data exchange between the digital twin and its physical counterpart, and analytics frameworks that enable simulation, optimisation, and assessment of alternative strategies under varying operational, economic, logistical, and environmental conditions, both current and future.

Core elements to realistically characterize IWT systems include:

- Fleet data: number of vessels, vessel length, beam, draught, carrying capacity, engine power and age, fuel type, fuel tank size, speed and other operational characteristics.
- Transport network data: routing options, class designations of waterway sections, bed levels, water levels, currents, presence of locks, bridges, inland ports and terminals, quays, (un) loading facilities, bunkering stations and modalities connections.
- Actual waterway usage: number of trips, cargo per trip, origins and destinations, route taken, vessel speed and congestion levels.
- Freight information: cargo types, volumes, origins, and destinations.

Data availability is critical for realistic modelling and validation of digital twins. The IWT community should therefore collaborate to make high-quality datasets accessible. While data and tools were historically developed within individual projects, recent open-source initiatives have improved sharing and reproducibility. Examples include network databases such as EURIS ⁽²⁾ and FIS ⁽³⁾, cargo datasets ⁽⁴⁾, open simulation frameworks (e.g., OpenTNSim ⁽⁵⁾ and OpenCLSim ⁽⁶⁾), AIS vessel trajectory, speed and navigation status data ^(7,8), hydrological information ⁽⁹⁾ and payload capacity. ⁽¹⁰⁾

Sharing such resources supports FAIR principles and allows modelling capabilities to accumulate across projects. Despite this progress, key data gaps remain, particularly in fleet composition, energy use and emissions, and detailed lock operations. Vessel log data would enable robust model validation, but commercial sensitivities limit access to it. Greater data sharing, supported by anonymisation or aggregation where needed, is therefore essential to improve model reliability and support digital twins for IWT.

An analytics framework, combining conceptual, physical, mathematical, optimisation, and AI-based models, uses validated data to replicate system behaviour, forecast outcomes, evaluate scenarios, and support decisions. For IWT, it should realistically represent vessel interactions with infrastructure (e.g., locks, bridges, and terminals) and key operational behaviours, such as route selection, travel time, draught–loading relations, energy use, and transport volumes. Model resolution should match the decision problem, while accumulating bidirectional data enables ongoing calibration and improved predictive accuracy for operational, tactical, and strategic decisions.

The feasibility of ZE and climate-resilient IWT is influenced by systemic challenges, including congestion at locks and terminals, unreliable transit times, droughts, ageing infrastructure, availability of alternative fuel, safety, fragmented data landscapes, and increasing sustainability requirements. Oversimplified assumptions risk obscuring system complexity, cascading effects, and transport capacity losses. ⁽¹¹⁾ To address this, the IWT community should prioritise understanding system behaviour and identifying key decision problems to guide digital twin functional requirements for specific decision contexts. Given the diversity of decision contexts, a single digital twin is unlikely to address all problems. Instead, modular architectures, interoperability, and collaborative development are essential to support decision-making and enable the transition toward ZE and climate-resilient IWT.

Evaluation of IWT systems from multiple perspectives

The evaluation of complex systems from multiple perspectives, considering scales, conditions, behaviour, and dependencies ⁽¹²⁾, offers a systematic approach for translating objectives into design requirements for an analytics framework. The process starts with a clear problem conceptualisation and proceeds with a structured assessment of requirements across these four perspectives.

Scales concern upfront decisions on minimal temporal (e.g., seconds to months) and spatial resolution (e.g., centimetres to kilometres), as well as aggregation methods that translate detailed data into higher-level representations (e.g., hourly to monthly, waterway segment to

province).

Conditions address the upfront decisions on external and environmental factors required to explain observed behaviour. In IWT, these include water depths, currents, waterway dimensions, and infrastructure elements such as locks, terminals and energy supply facilities. This perspective influences both model selection and output design, determining which environmental attributes must be represented.

Behaviour requires upfront decisions on the level and type of human behaviour the analytics framework should capture. Key design choices include representing individual agents versus collective behaviour, dynamic versus steady-state processes, and specific operational strategies (e.g., constant speed versus constant power in shallow water, fleet deployment responses to unmet transport targets, and route selection criteria).

Dependencies address upfront decisions on the kind of interactions the analytics framework should be able to resolve, such as queue formation when capacity is exceeded, cascading delays caused by tidal windows, or the system-wide effects of alternative locking strategies.

These perspectives define progressively more complex and cumulative requirements. Addressing them early in the design process reduces costly iterations during development. Without such upfront structuring, even advanced digital twins for IWT may fail to provide actionable insights or operational decision support.

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