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Vessel Data Visions for Decision Making

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Vessel Data Visions: Data Management Considerations for Optimum Life Cycle Costs

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Dean Vučinić

Abstract

This paper introduces the Ship Digital Twin, employing a knowledge graph database and deep learning to advance the operational and maintenance efficiencies of maritime vessels. At the core of this initiative are "vessel visions," customised views of ship data tailored for specific maritime stakeholders like class societies, flag states, ship operators, port authorities and others. Each vision is crafted through a domain-specific language (DSL), facilitating stakeholder-specific interfaces that access and interpret the digital twin's data effectively. The knowledge graph database underpins these visions by structurally encapsulating ship data, enabling complex queries and dynamic data relationships that support precise decision-making processes. This system not only refines life cycle costs but also enhances safety and environmental sustainability through proactive management. This integration facilitates a holistic view of ship operations, supporting the optimisation of life cycle costs and improving safety and environmental sustainability. Through the digital twin, stakeholders including ship owners, operators, and regulatory bodies gain unprecedented insights, driving efficiencies and reinforcing industry standards. The paper details the development of these specialised visions, the application of deep learning for robust data analysis, and the transformative impact on maritime industry standards.

Keywords: ship; data governance; digital twin; maintenance management; life cycle costs

Introduction

The maritime industry is experiencing a transformative shift with the advent of Digital Twin technology, which creates virtual replicas of ships for real-time monitoring and optimisation. This paper introduces the Ship Digital Twin framework, utilising a knowledge graph database to enhance operational and maintenance efficiencies and improve data governance.

Central to this framework are "vessel visions," tailored views of ship data for specific actors such as class societies, flag states, ship operators, and port authorities. These customised interfaces, created using a domain-specific language (DSL), allow actors to effectively access and interpret the Digital Twin's data.

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The knowledge graph database structures ship data to support complex queries and dynamic relationships, enabling precise decision-making. By organising data in a highly interconnected and accessible manner, the knowledge graph enhances data governance. The benefit of using a Knowledge Graph database is that both structured, semi-structured and unstructured data made accessible and can contribute to the decision-making process.

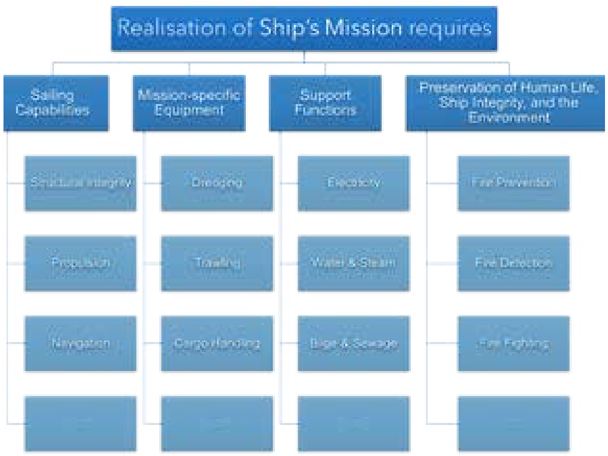
The Ship Digital Twin not only optimises life cycle costs but also enhances safety and environmental sustainability. This paper details the technical architecture, development of data mappings (which in turn specify domain-specific languages) and the implementation of the knowledge graph database.

The Ship (internal) Vision

Let's start our data governance journey by the knowledge of the ship as the central piece (node) of the Ship Digital Twin Framework.

The ship represents a complex technical installation. We'll have to see the ship as a collection of processes (functions) needed to realise the ship's mission (her purpose).

The Ship's Functional Decomposition will provide us with substantially structured data regarding ship's systems and their interdependencies (relationships). This fairly static information will form the skeleton of Ship's Digital Twin. Every item will belong to one of the systems as shown below [1].

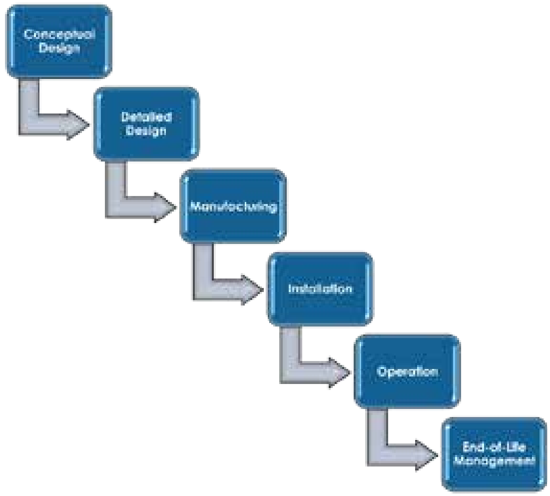


The functional decomposition is highly dependent of the ship type. These structured data should be enriched with scientific studies going from Numerical (e.g., FEM models) hull models, physical 3D models (e.g., towing tank models) to process models Reliability Block Diagrams (RBD) as proposed by [7], all to be kept in the Digital Twin Framework

The Ship (Temporal) Vision Ship's Life Cycle Phases

The life cycle of a ship encompasses several critical phases [2], each with specific activities and objectives aimed at ensuring the vessel's optimal performance, safety and compliance throughout her operational life. Last but not list the overall Lifecycle Costs (LCC) [3] are key to our optimisation and a primary factor in our decision making.

We use the life cycle to show the dynamic, transformative, time-based nature of the Ship Digital Twin. A typical life cycle is shown next:



The following sections outline these in terms of data visions:

Conceptual Design

Often this initial phase commences with research and exploration. We investigate new materials, propulsion systems and technologies applicable to shipbuilding and we conduct studies on hydrodynamics, fuel efficiency and environmental impact. The data in this phase are very general and broad in nature and as such very unstructured.

Once the explorative phase is sufficiently rounded, as this process continues, the initial Concept of the Ship is developed and evaluated, defining the vessel's purpose (e.g., cargo, passenger, research), size, capacity and general layout.

Detailed Design

Enter Detailed Design developing Engineering Plans and specifications. Many design decisions have been taken and the actual Digital Twin is starting to take shape and a vast amount of data is generated as: detailed engineering drawings, 3D models and prototypes. Although highly structured these data was historically not perceived as structured as being on paper. Fortunately, today with progresses in knowledge management, this is not the case anymore and the semantic data is stored natively via Model Based Definition tools like MBDVidia [8].

Manufacturing

Once the design is rounded, at least for the hull we can begin ship construction in a shipyard, including sourcing materials, fabricating parts and assembling the vessel. Today, with NC machines and highly automated manufacturing processes the data is exchanged flawlessly among machines. At this point, the design data are transposed into a physical product – the ship. Rigorous quality control is implemented throughout the process.

Installation

Once the ship is launched, outfitting her with all the designed equipment and systems is finalised. Sea Trials are usually the final quality control checkpoint prior to delivering the ship to the Ship Owner. In order to ensure it is ready for operation, this phase will include final adjustments, crew training and handover procedures. This is the final validation that the envisioned design was followed and its realisation the physical product is conform.

Operation

The Ship is put into active service and she performs its designated functions (e.g., transporting goods, carrying passengers).

This phase is usually the longest and represents the Useful Life of the Ship. It is also the source of a vast amount of data, which are highly unstructured (textual reports, photo snapshots, sensor readings etc.). This is also the phase that can benefit the most of AI in general and deep learning in particular, to guide our decision making with tools based on LLM's as proposed by Neo4j [12] and/or Cambridge Semantics [13];

End-of-Life Management

End-of-Life Management includes usually decommissioning, however we can envision Life Extension and other sustainability options. We can explore ways to extend the ship's life through refurbishing, retrofitting with new technologies, or repurposing for different uses. For example, a VLCC can be converted to an FPSO. Of course in terms of data this will give birth to a new digital twin for the FPSO, for which the VLCC historical data shouldn't be of much use, however it will be of vital value for future VLCC designs.

In summary, we listed the different phases of a single ship. However, the real power lies in the recursive use of previous life-cycles in the data analysis of future ones:

In this way the repetitive nature of one phase's data vision becomes available for the data analysis, by creating a Domain Specific Language (DSL) i.e. an ontology that will be stored in a Knowledge Graph.

In addition to the temporal component of ship data captured by the ship's life-cycle phases, the Ship Digital Twin framework must accommodate interactions with various actors, each with specific data requirements essential for their roles

The Ship's Actors and their Data Visions

In addition to the temporal component of ship data captured by the ship's life-cycle phases, the Ship Digital Twin framework must accommodate interactions with various actors, each with specific data requirements essential for their roles. These requirements vary in their level of structure, from highly structured scientific models and studies to more unstructured formats like textual inspection reports.

The following sections detail these actors and their data needs:

Environment

Environmental actors focus on the impact of the ship's operations on the marine and atmospheric environment, including emissions, waste management and ecological footprint.

Data Requirements:

- Structured: Emissions data (CO2, NOx, SOx), fuel consumption.
- Semi-Structured: Waste generation and disposal methods, ballast water management.
- Unstructured: Impact on marine biodiversity.

Society

Societal actors are concerned with the broader impact of the ship's operations on communities and economies, including employment, safety and economic contributions.

Data Requirements:

- Structured: Employment data (number of jobs created), economic impact (contribution to local economies).
- Semi-Structured: Safety records and incident reports.
- Unstructured: Community engagement and development activities.

International Maritime Organization (IMO)

The IMO regulates shipping, focusing on safety, environmental concerns, legal matters, technical cooperation, maritime security and efficiency.

Data Requirements:

- Structured: Compliance with international regulations and conventions (MARPOL, SOLAS, etc.), emission control data.
- Semi-Structured: Safety management systems, port state control inspections.
- Unstructured: Incident and accident reports.

Port State

Port state authorities ensure foreign ships docking at their ports comply with international and local regulations through inspections and enforcement.

Data Requirements:

- Structured: Compliance with port regulations, arrival and departure schedules.
- Semi-Structured: Ship inspection records, cargo documentation.
- Unstructured: Security measures and protocols.

Flag State

The flag state is the country under whose laws the ship is registered. It ensures the ship adheres to international and national regulations.

Data Requirements:

- Structured: Ship registration details, compliance with national and international regulations.
- Semi-Structured: Crew certification and training records, maintenance and inspection records.
- Unstructured: Safety and security compliance.

Classification Society

Overview: Classification societies establish and maintain technical standards for the construction and operation of ships. They conduct surveys and issue compliance certificates.

Data Requirements:

- Structured: Structural integrity and stability data, safety equipment and procedures.
- Semi-Structured: Machinery and electrical systems, survey and inspection reports.
- Unstructured: Certification status and history.

Ship Builder

Shipbuilders are responsible for designing and constructing ships, ensuring vessels meet required standards and specifications.

Data Requirements:

- Structured: Design specifications and blueprints, material and component specifications.
- Semi-Structured: Construction progress and milestones, quality assurance and testing data.
- Unstructured: Compliance with classification society standards.

> ***The Ship Digital Twin framework leverages a knowledge graph to organise and manage data, with the storage method depending on the level of data structure***

Ship Broker

Ship brokers facilitate the buying, selling and chartering of ships, acting as intermediaries between ship owners and charterers or buyers.

Data Requirements:

- Structured: Ship specifications and capabilities, market conditions and trends.
- Semi-Structured: Charter party agreements, sale and purchase contracts.
- Unstructured: Operational performance data.

Ship Owner

Ship owners manage the financial, operational and regulatory aspects of the vessel.

Data Requirements:

- Structured: Financial performance data, operational efficiency and cost data.
- Semi-Structured: Compliance with regulations, maintenance and repair records.
- Unstructured: Crew management and performance data.

Ship Operator

Ship operators handle the day-to-day operations of the vessel, ensuring efficient and compliant functioning.

Data Requirements:

- Structured: Voyage planning and execution data, fuel consumption and efficiency.
- Semi-Structured: Cargo handling and logistics, real-time operational data (speed, position, weather conditions).
- Unstructured: Crew management and welfare.

The Ship Digital Twin framework leverages a knowledge graph to organise and manage data, with the storage method depending on the level of data structure. Structured data, such as emissions statistics or compliance records, can be directly transposed into nodes and relationships within the knowledge graph. Semi-structured data, including maintenance records and inspection reports, can be mapped to the graph with some preprocessing to standardise formats and ensure compatibility. In contrast, unstructured data, such as textual descriptions in inspection reports or community engagement activities, will be stored in a vector store model using embeddings. This approach enables advanced processing and analysis using Large Language Models (LLMs), which can extract insights and support decision-making processes.

Vessel Position & Status

Two key data elements (or nodes in the underlying Knowledge Graph) in the Digital Twin Framework are:

- **Ship Position**, attributes: Latitude, Longitude, Timestamp, Speed Over Ground (SOG), Course Over Ground (COG), etc.
- **Ship Status**, attributes: Status Type, Timestamp, Environmental Conditions, etc.

Ship Position (Based on AIS)

The ship's position is a crucial data element in the digital twin framework, primarily sourced from Automatic Identification Systems (AIS). Some popular providers of AIS services are:

- MarineTraffic [9],
- VesselFinder [10],
- Spire Global [11],

The Digital Twin framework will be connected to these data streams.

Ship Status (As per IMO)

The ship's status, as defined by the International Maritime Organization (IMO), provides a clear description of the vessel's operational condition and lifecycle stage. The usual Statuses are: Under Construction, In Service - At Sea, In Service – Port, In Service - At Anchor, Casualty, Repair, Laid up, Broken up, Total Loss. This can further be refined, if needed.

> *The objective of the Ship's Digital Twin Framework is to create a data store for the physical ship, capturing real-time data from various sources to provide a comprehensive view of its current state and environment*

Absorbing External Data in the Ship Digital Twin Framework

The objective of the Ship's Digital Twin Framework is to create a data store for the physical ship, capturing real-time data from various sources to provide a comprehensive view of its current state and environment. In addition to the presented "Ship - Actor – Lifecycle phase" triad, the framework will record other external data streams as shown below:

A non-exhaustive list of external data sources that will enrich the Ship digital twin:

Port

Information on the port, including the number of mooring points, facilities available and loading/unloading equipment.

Shipyard

Data from the shipyard covering maintenance schedules, repair history and availability of dry docks.

Sea State

Real-time data on wave height, wave period and sea surface temperature, providing a comprehensive view of current sea conditions.

Weather

Integration of weather data streams [11], including temperature, pressure, wind speed [4] and direction.

Crew

Detailed information about the crew, including individual skills, experience and certifications.

Other

The Digital Twin Framework is designed to accommodate additional data sources as needed. **These could include cargo information, fuel consumption data [5], and other metrics.**

Data Ingestion and Integration

The digital twin will utilise a data ingestion platform capable of handling multiple data streams simultaneously. This platform integrates data from IoT sensors, external databases, and manual inputs.

IoT Sensors and Devices

Sensors placed on the ship, at ports, and in shipyards continuously collect data on various parameters such as structural integrity, equipment status, and environmental conditions.

APIs and External Data Sources

Weather data, sea state information, and other external data are ingested through APIs from trusted sources like meteorological services and marine agencies.

Data Processing and Storage

The ingested data is processed in real-time to ensure accuracy and relevance. A robust storage solution: the Neo4j knowledge graph [12] is implemented to store historical data for analysis and trend identification. It was selected in particular because it can store unstructured text (vector database), natively.

Integration

The digital twin as an integrator of all the data streams presented in this paper lays a sound foundation for:

The Ship Digital Twin framework captures both static and dynamic aspects of a ship's life cycle, enabling a holistic view of operational and maintenance needs

- Real-Time Monitoring
- Predictive Maintenance
- Simulation and Optimisation
- Enhanced Decision-Making

With comprehensive data at their fingertips, decision-makers can make informed choices that enhance safety, efficiency and profitability.

Conclusions

The implementation of Digital Twin technology in the maritime industry marks a significant advancement in ship operations and management. This paper introduced the Ship Digital Twin framework, leveraging a knowledge graph database to enhance improve data governance and provide tailored data views for various stakeholders, such as: class societies, flag states, ship operators and port authorities.

Central to this framework are "vessel visions" that enable actors to access and interpret relevant ship data effectively. By structuring ship data into a highly interconnected knowledge graph, the framework ensures precise decision-making and optimises life cycle costs.

The Ship Digital Twin framework captures both static and dynamic aspects of a ship's life cycle, enabling a holistic view of operational and maintenance needs. Recursive use of data from previous life cycles further enhances predictive capabilities and decision-making.

Data is structured according to stakeholders' specific requirements, ranging from structured data to semi-structured and unstructured data. This data is integrated into the knowledge graph and vector store model, allowing advanced processing using Large Language Models (LLMs).

Key data elements—ship position and ship status—are essential for the framework. By connecting to external data streams, the framework creates a comprehensive digital representation of the ship in her environment.

The data ingestion platform enables seamless integration of IoT sensors, external databases, and manual inputs, ensuring real-time processing and storage. This supports real-time monitoring, predictive maintenance, simulation, optimisation and enhanced decision-making.

In conclusion, the Ship Digital Twin framework integrates diverse data sources into a cohesive digital model, improving operational efficiency and safety while supporting sustainability and cost optimisation. As the maritime industry evolves, the Digital Twin framework will drive innovation, enhance data governance and ensure the longevity and efficiency of maritime assets.

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