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METHOD ARTICLE

Developing a digital twin for the ammonia fuelling system structure: A systems approach

[version 1; peer review: 2 approved with reservations]

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Abstract

Waterborne transport accounts for approximately 25% of the European Union's greenhouse gas (GHG) emissions, a share expected to grow with increasing global trade. To meet the EU's goal of a 90% reduction in GHG emissions by 2050, alternative fuels and innovative technologies are essential. Ammonia (NH_3) has emerged as a promising zero-carbon fuel; however, it requires nearly three times the storage volume of conventional fuel oil. The NH3CRAFT project addresses this challenge by aiming to design and demonstrate safe, sustainable large-scale NH_3 storage—1,000 m^3 at 10 bar—aboard a 31,000 Deadweight tonnage (DWT) vessel.

The project employs a digital platform that integrates computational models, simulations, and real-time sensor data—including AI-enabled inspections—to support the development of a Digital Twin (DT). While DTs are well-established in the automotive and aerospace industries, their use in maritime applications is evolving, especially in the areas of structural health monitoring (SHM) and predictive maintenance. This study applies a systems engineering approach from an SHM specialist's perspective to assess the feasibility of implementing a DT specifically for the NH_3 fuelling system.

Key technical gaps and system-level considerations for NH_3-specific SHM integration into the DT were identified through collaboration with project partners. These include challenges in sensor deployment, data fusion, and the need for high-fidelity modelling of NH_3 behaviour under dynamic maritime conditions. The study outlines requirements for building a hard system capable of ensuring long-term structural integrity and safety.

The development of a DT for the NH_3 fuelling system presents significant potential to enhance SHM and operational safety. A

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Approval Status ? ?

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Any reports and responses or comments on the article can be found at the end of the article.

strategic decision remains pending within the consortium regarding the full-scale implementation of the DT. This study provides a foundational framework to support that decision and future DT development in maritime NH_3 applications.

Keywords
digital twin, ammonia fuelling, structural health monitoring, predictive maintenance



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Introduction

Waterborne transport currently accounts for a quarter of the European Union's (EU) greenhouse gas (GHG) emissions, and this figure continues to rise as demand increases[1,2]. To meet the target of 90% reduction in emissions by 2050[1,3], substantial investment will be required, as zero-carbon fuels require the development of new solutions involving the adoption of new technologies, logistics, and operations. Such a fuel is ammonia (NH3), while it is carbon-free; it presents specific challenges in its use. Storage is a major issue because its liquid form requires almost three times the space of fuel oil for equivalent use[4].

To tackle this storage challenge, the NH3CRAFT project was launched to fully design, engineer, develop, and demonstrate a next-generation sustainable and commercially attractive technology for the storage of high quantities of NH_3 as a marine fuel. This process will be realized by developing new design solutions that will offer the feasibility of 1,000 m^3 storage of liquid NH_3 at a pressure of 10 bar and demonstrating it on a 31,000 Deadweight Tonnage (DWT) multi-purpose vessel.

As a core work package of the NH3CRAFT project, an innovative digital platform is being developed, which will be able to integrate all core simulations and models through a digital interface, and will develop an engineering system matrix and specifications for the fuel storage, supply and piping, monitoring and venting subsystem. An illustration of the digital platform is presented in Figure 1[5]. On-board sensors installed by project partners, including tablet-based inspection processes, Artificial Intelligence (AI) enhanced inspection data analysis, fuel consumption, machinery performance, and hull fouling, will be linked to the digital platform through a standardized interface along with live monitoring of the NH_3 for future development of a Digital Twin (DT).

DT technology is a virtual representation of physical systems and has gained significant attention for its ability to improve efficiency, reduce costs, and enhance decision making across various industries[6]. Although DTs have seen the most advanced applications in the automotive and aerospace sectors, their adoption in the maritime industry has been comparatively slow. However, there is growing evidence that DTs are being actively developed and applied at various stages of shipbuilding and operations. Applications in ship design, construction, propulsion management, and structural integrity monitoring have demonstrated the increasing potential of DTs to enhance efficiency and safety in the maritime sector[7].

In particular, significant advancements have been made in the monitoring of structural integrity in ships. A notable joint industry-academia project in Japan[8] focused on developing DTs for ship hull monitoring based on an already established technology[9]. These DTs are designed to provide real-time data on the hull condition and address uncertainties in the load and strength measurements. The goal is to evaluate the cumulative fatigue damage caused by wave loads, with DTs continuously updated using inputs from strain gauges, accelerometers, temperature and pressure sensors, and environmental data (e.g., wave height and wind speed). Regular inspections further supplemented these updates. A key challenge in this project is the limited number of strain sensors, which necessitates the development of new methods to assess the stress in areas lacking direct strain gauge coverage. Fiber Bragg grating (FBG) sensors, capable of measuring strain, acceleration, and pressure, have been integrated into the models and validated on several bulk carriers. Future work will aim to merge the hull DT with others covering propulsion, navigation, and construction systems, creating a comprehensive decision-making tool for risk-based maintenance.

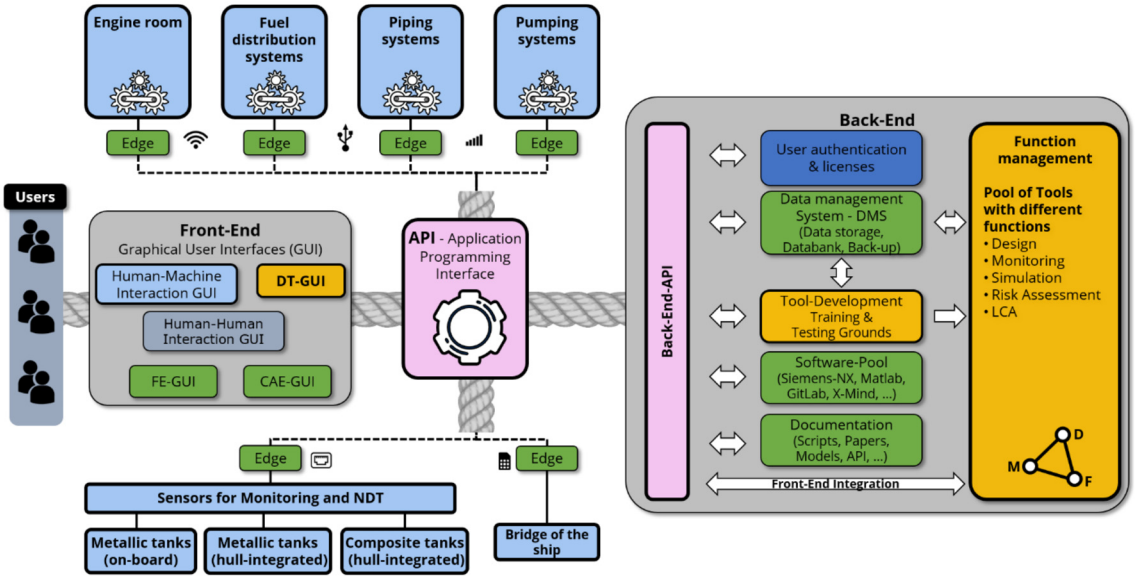

Figure 1. Schematic of Digital Platform for the NH3CRAFT project[5].

The operational phase of ships can also benefit from DTs, particularly in terms of predictive maintenance, fault detection, system monitoring, performance prediction, and conducting virtual tests[10]. Additionally, DTs in the broader marine industry, including fishing, offshore power, and deep-sea mining, are proving to be valuable. These tools assist in decision making across the design, construction, operation, and maintenance phases of ships. Notably, integrating DTs with Artificial Intelligence (AI) is advocated to address the unique challenges of the maritime environment[11].

In the demonstrator vessel, this study advocates additional Structural Health Monitoring (SHM) sensors for the NH_3 fuelling system as a functional element of the DT that will be developed in the future for the vessel.

In this paper, a 'Systems approach' is used to lay out the issues and the potential technical gaps in developing a DT for the NH_3 fuelling system. These issues should be discussed with project partners, which would provide guidance in developing a DT that can meet the requirements of all project partners in future projects. The author of this paper is a structural health monitoring specialist; therefore, this paper is biased towards this technology.

Methods – the systems approach

The design, development, and operation of any DT system are inherently complex because they require interactions not only between the physical components of the system but also between the DT, humans, and the environment. A useful approach to study these interactions and their resulting interdependencies is the systems approach, which is recommended by DNV[12] for qualifying Artificial Intelligence (AI) systems.

A system can be viewed as a process with defined inputs and outputs that functions within a well-defined boundary. Outside this boundary lies an environment that can impact the system's function, but is not influenced by it. In addition, these systems interact with other ecosystems. Systems are typically structured in a hierarchy of sub-systems, where each level below answers the "How" to the "What" at the level above. One key characteristic of systems is "emergence," where complex systems exhibit properties that their individual components lack and that only arise when those components interact as a whole.

Given that human factors play a critical role in complex systems like DTs, it is helpful to distinguish between 'Soft' and 'Hard' systems. A 'hard system' is technology-centered and physical in nature, typically analyzed using linear thinking and reductionism, focusing primarily on function and performance. In contrast, a soft system is centered around human activities and employs circular thinking, where feedback enables the system to evolve over time. This approach considers the system as a whole and emphasizes the interactions between its components and the environment, focusing primarily on purpose.

This paper focuses solely on the discussion of the development of a hard system for DTs.

Results

The hard system for DT of NH3 fuelling system

Overview

Based on the DNV standard[13], a hard system schematic for DT is shown in Figure 2. A detailed discussion of each item is presented in the following sections.

Inputs

Monitoring data streams

The key to the function of the DT in terms of monitoring data streams is the selection of SHM sensors.

As previously mentioned, sensors that measure strain and vibration are commonly used to monitor ship structures globally. Locally, the NH_3 fuelling system, which is more susceptible to corrosion damage and is subjected to internal pressure, can use permanently fixed ultrasonic sensors to measure wall loss and acoustic emission sensors to detect crack initiation or growth.

In addition, process monitoring sensors are required for the fuelling system's Supervisory Control and Data Acquisition (SCADA) to transmit data regarding the temperature, pressure, and flow rate in piping and tanks. There are pumps in the NH_3 fuelling system that can be monitored using vibration sensors to detect misalignments or imbalances that might result in leaks or mechanical failures. Similarly, vibration sensors can track piping vibrations caused by turbulence, blockages, or weak joints as well as monitor valve vibrations to ensure smooth opening and closing. Finally, to consider the influence of the external environment, sensors that can measure ambient temperature, wind speed, wave height, etc. should be included.

By analyzing these data from the sensors, the system's fuel delivery can be optimized, potential disruptions to ammonia flow can be prevented, and the risk of ammonia leakage can be minimized.

Metadata

Metadata provide a crucial context to the monitoring data, without which results from the analysis of sensor data may not have any meaning. The Metadata describe the characteristics, settings, and conditions under which the sensors operate and enable better integration within the DT systems. Some key information should be sensor identification (ID/Name, type, manufacture, model number, etc.), functionality (measured parameter, unit, accuracy, and resolution), location, calibration (calibration standard, last calibration date, next calibration due, etc.), and operational context (operational environment, ship speed and direction, loading intervals, communication protocol, etc.).

Documentation

Documentation plays a critical role as an input for the effective implementation of DT in an NH_3 fuelling system. These include system design specifications that provide a detailed architecture of the fuelling system, including pump layouts, pipeline diagrams, and control systems. Technical datasheets are essential, as they offer information on the capacities, operational

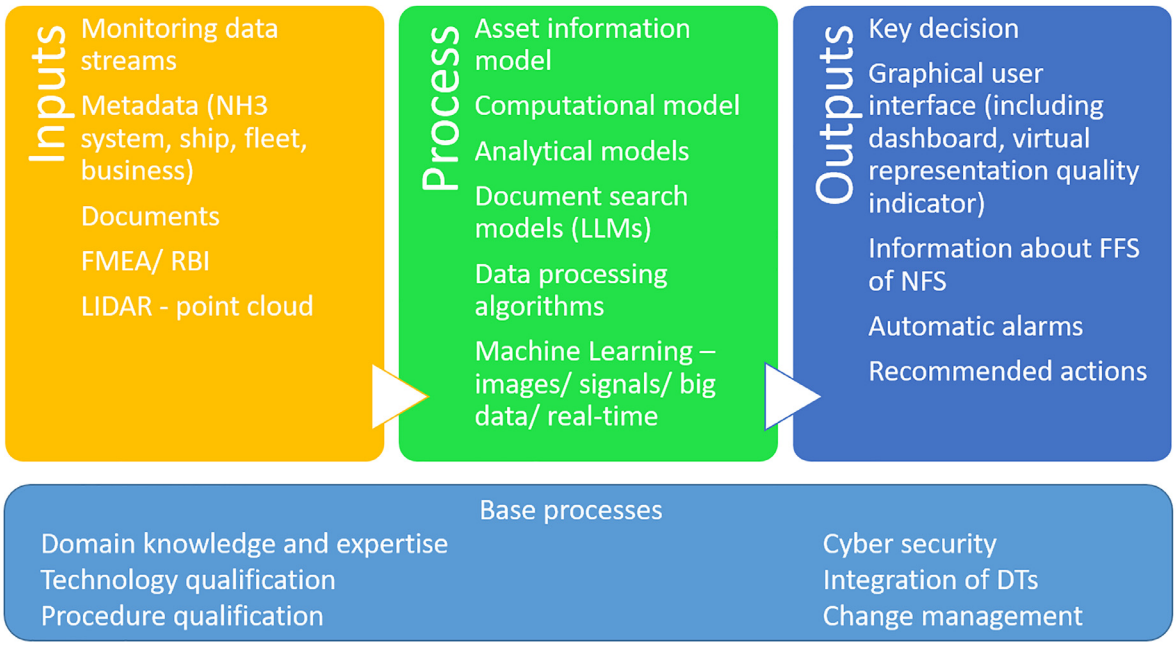

Figure 2. Hard systems model of the digital twin[13].

ranges, and materials of critical components (pumps, valves, sensors, and storage tanks). Safety and compliance documents, such as risk assessments, can provide an in-depth analysis of potential hazards within the NH_3 fuelling system and highlight the role of DT in risk mitigation and ensuring regulatory compliance. Operations and maintenance documents are equally important, encompassing step-by-step operating procedures for the safe and efficient functioning of the system along with maintenance manuals that outline both routine and corrective maintenance practices for various components. Additionally, these documents include inspection reports, maintenance logs, and event histories such as accidents or repairs. Together, these documents form the foundation for ensuring the proper design, operation, safety, and maintenance of the NH_3 fuelling system while supporting the functionality and accuracy of the DT.

Failure mode and effect analysis

A Failure Mode and Effects Analysis (FMEA) identified wall thinning, embrittlement, and cracks as potential failure modes in the NH3 fuelling system, specifically in storage tanks, straight piping sections, and connections.

Wall thinning, caused by material degradation or erosion from high-velocity ammonia flow, can weaken structural integrity, leading to leaks or failure. Another failure mode is embrittlement, which is triggered by exposure to low temperatures, chemical interactions, or stress, and can reduce material ductility, making metallic components prone to sudden fractures. In terms of cracks, whether initiated by manufacturing defects, fatigue, thermal cycling, or mechanical stress is also a critical failure mode. Cracks in storage tanks as well as in straight piping sections and connections can propagate over time, leading to leaks, loss of containment, or even ruptures.

A risk-based inspection (RBI) assessment was performed for metallic storage tanks following API RP 580[14]. This identified external corrosion under insulation, coating breakdown, and NH3 embrittlement as the primary damage mechanisms.

Point cloud models of the structure

3D maps of a structure created using Light Detection and Ranging (LIDAR) are now being used to create a virtual copy[15]. Virtual reality images can be tagged with information, such as inspection reports and photographic images, thus providing a direct context for inspections. An inspector can stand in front of the structure and visually compare it with how it appears in a photograph viewed on a tablet computer linked to the virtual copy. On large structures, such as bridges, inspections are performed with drones, which use ML to detect anomalies caused by corrosion and fatigue. For pipework, LIDAR-created 3D images also help overcome the frequent problem of pipework CAD drawings (or PIDs) not matching, because of modifications during fabrication.

Process

Asset information model

The Asset Information Model (AIM) is a critical component in the creation and operation of a DT for an NH_3 fuelling system. It serves as a centralized repository that compiles all data and information necessary to support asset management and optimize the performance of the fuelling system. AIM can provide both graphical and non-graphical data as well as essential documentation and metadata, ensuring a holistic digital

representation of the physical system. For an NH_3 fuelling system, AIM can feature detailed point-cloud models that visually map components such as piping, pumps, valves, and storage tanks. It should also incorporate the original design specifications that outline the system architecture and operational parameters. Beyond the design data, AIM integrates records of repair work, such as valve replacements or pipe repairs, as well as historical operational performance data captured from SCADA systems.

Computational model

A computational model is a mathematical framework used to simulate and analyze the behavior of complex systems. By leveraging extensive computational resources, these models solve intricate equations that provide a deeper understanding of the system dynamics, interactions, and potential failure modes through computer simulations. For an NH_3 fuelling DT system, the Finite Element Analysis (FEA) models will be used as the computational model to simulate the structural integrity and performance of critical components, such as piping, storage tanks, pumps, and valves. Incorporating FEA results with real-time data from SCADA systems and other sensors can offer valuable insights into how these critical components behave under various conditions. These insights will provide a dynamic representation of the health of the system, enabling engineers to predict potential issues and proactively address them.

Analytical models

Analytical models rely on mathematical calculations to evaluate the behavior and performance of systems and determine whether a system is fit for service. In an NH_3 fuelling system, Engineering Critical Assessment (ECA) is an essential analytical method to ensure the integrity of the NH_3 piping system. The ECA process includes identifying and assessing potential flaws, such as cracks, corrosion, or material defects, that could compromise the integrity of the system. By applying the principles of fracture mechanics, ECA calculates whether such defects are acceptable within the context of the material properties of the system (e.g., fracture toughness and tensile strength), operational pressure, temperature variations, and the expected lifecycle of the system.

Document search models

Large-language models (LLMs) are gaining significant attention because of their transformative capabilities in generative AI, enabling tasks such as text generation, summarization, translation, and answering complex questions. LLMs can be leveraged to interrogate library documents within the DT framework, thereby providing efficient access to critical information. This means that, instead of manually searching through extensive documentation or datasets, users can query the LLM in natural language to extract relevant insights, such as operational procedures, maintenance schedules, or technical specifications.

Data processing algorithms

These could be subsystems of the DT, incorporated with 'Edge computers' for specific 'smart sensors. ' Examples include:

- Vibration analysis algorithms investigate the patterns in vibration signals to detect modal changes that are indicative of failures in machinery and structures.
- Image analysis algorithms that extract meaningful information from images, for example the presence of surface corrosion.

Machine learning – images/signals/big data, real-time

The sensors in the NH_3 fuelling system produce extensive data over prolonged periods. To derive valuable insights from these data for computational and analytical models, the application of ML is critical. ML employs advanced statistical algorithms to detect trends, patterns, and correlations within the data, helping identify damage mechanisms in the NH_3 system. Integrating ML into DT requires a robust and well-planned work program, encompassing data pre-processing, model training, and validation. Specialized expertise in computational science and data analytics is necessary to effectively implement and optimize these algorithms.

Technology gap analysis

Based on the above information, from an SHM point of view, efforts have been made to identify possible technology gaps that can be foreseen in developing a DT for the fuelling system and corresponding actions. The outcomes are summarized in Table 1. Note the importance of finding commercially available off-the-shelf (COTS) solutions.

Outputs

Key decisions

Each DT should be linked directly to a key decision-making process to ensure its effectiveness and relevance. The recommended practice for qualifying DTs outlined in DNVGL-RP-A20[13] suggests that key decisions, referred to as Functional Elements (FEs), should be organized into a hierarchical structure. In this hierarchy, lower-level FEs contribute to and support the achievement of broader, higher-level FEs. This structure enables a clear and logical flow of information, ensuring that the outputs of a DT directly influence the critical decision-making processes. For an NH_3 fuelling system, the FEs addressed by the DT can include various critical tasks, such as the identification, location, and sizing of damage in components such as piping, valves, and storage tanks. These elements can be fed into higher-level decisions, such as predicting system failures, determining life extension strategies, assessing fitness-for-service, and planning maintenance or repair schedules.

Graphical user interface, automatic alarm and recommended actions

A Graphical User Interface (GUI) serves as the point of interaction between humans and computers. This interface can be accessed via desktop computers and tablets depending on the user's preferences and needs. The dashboard in the GUI presents various types of visual data in a simplified, easy-to-understand format. To ensure the quality of the data, the dashboard should include a quality indicator that assesses the reliability of the displayed information. A common approach is a 'traffic light' system, where:

- Green indicates that the information is of sufficient quality for key decision-making.
- Yellow warns that the data may be of insufficient quality and requires caution when used for decisions.

Table 1. Possible technology gaps analysis in developing a DT for the NH3 fuelling system and the corresponding actions.

Technology	Description	Current function	Required function	Action
Smart SHM sensors	Sensor systems with software included within local 'Edge computers'	Sensor data processed separately, then analyzed and interpreted manually	Sensor data processed analyzed and interpreted locally on edge computers	Feasibility study, including search for COTS components, technology qualification
Data fusion	Combining data from different sources, for example AE sensor data with load sensor data	Data analyzed separately	combined	Selection of data to combine. Feasibility study
Embedded SHM sensors	Fiber optic sensor embedded in composite storage tanks	Optical Bragg gratings used to measure strain, temperature, pressure and detect transients such as acoustic emissions	Optic fibers	Feasibility study, including search for COTS components, technology qualification
Machine Learning	Learn from SHM sensor data, including past data to identify patterns and make predictions.	Use of LLMs to interrogate databases of documents in DT	Automatic interpretation of sensor data to give information about structural integrity of NH3 fuelling system	Feasibility study, selection of data, big data analytics, statistical analysis.

- Red indicates that the information is of poor quality and should not be used for critical decisions.

In addition, the system should be designed to prioritize automatic alarms that promptly notify users of critical issues, enabling swift responses to potential risks. Furthermore, the system should highlight recommended actions to address these issues based on the output of key decision-making processes, ensuring that the most effective solutions are clearly communicated and can be swiftly implemented.

Base processes

Domain knowledge and expertise

Building an effective DT for an NH_3 system requires expertise spanning multiple areas, including, but not limited to, chemical engineering, structural design, mechanical engineering, structural integrity management, control systems, data science, safety and risk management, ML, Non-Destructive Testing (NDT), simulation, and modelling. Collaboration across these domains is essential to ensure that DT accurately represents the system's physical and operational characteristics and provides reliable data for decision-making. It should be noted that the wide range of relevant knowledge mentioned can be covered by project partners, but there is a lack of expertise in the operation of the NH3 system.

Technology qualification

To gain trustworthiness, all technologies used by DT must be qualified. This process provides evidence that a technology will function within specified operational limits with an acceptable level of confidence. The methodologies that can be used are outlined in DNV A203[16]. This uses an iterative approach, as shown in Figure 3, where the technology is broken down into components that can be categorized on a scale ranging from COTS to novel, and the level of qualification set accordingly. Technology Reference Levels (TRLs) are useful marker[17]. The risk of each component not performing as required was assessed, and a work plan was developed to provide evidence that mitigates this risk. The qualification process can be staged using an iterative approach, with each cycle concluded at a different milestone. This milestone could be based on the Technology Reference Level (TRL).

Procedure qualification

Procedure qualification is the process of providing evidence of the SHM and NDT capabilities. It can include the results of capability evaluation exercises, feedback from site experiences, applicable and validated theoretical models, and physical reasoning. It should include trials on deliberately defective test pieces and mockups. A suitable methodology is provided by European Network for Inspection and Qualification (ENIQ)[18]. The methodology identifies the essential influencing parameters. An example of the influencing parameters in an Acoustic Emission (AE) monitoring system is shown in Figure 4.

Cyber security

Cyber security and protection of DT from malicious attacks is essential. Cloud-based systems are especially vulnerable and may rule out their use entirely. Therefore, significant human factors must be addressed.

Interfaces

Interfaces between different elements of the DT and co-systems are key issues that need to be addressed. For example, data from different sensor systems and their associated metadata (sensor location, characteristics, etc.) are normally processed, interpreted, and stored using proprietary software. Sharing data from

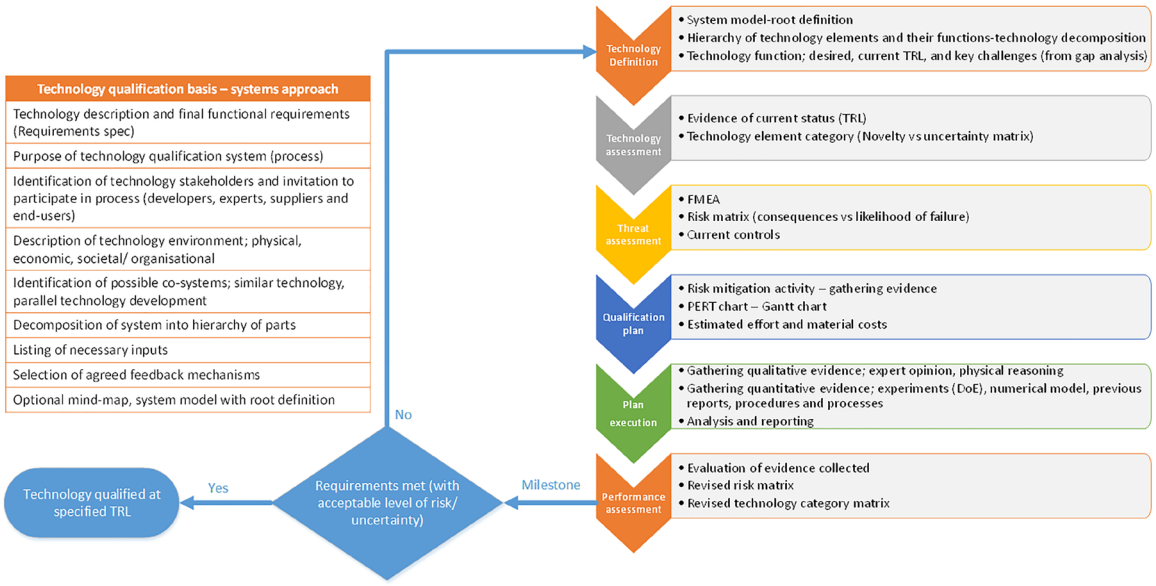

Figure 3. Systems approach to Technology Qualification.

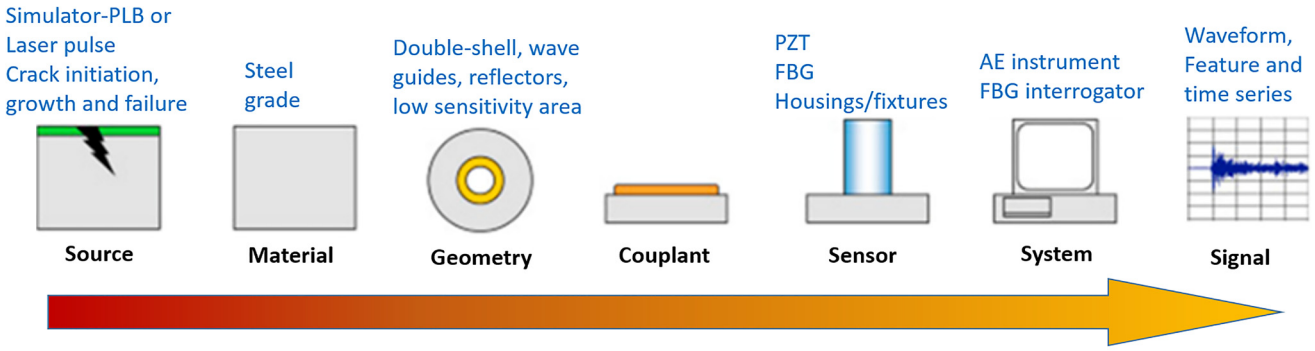

Figure 4. Essential influencing parameters in Acoustic Emission monitoring.

different systems is difficult, which is an issue that requires further research.

Open-source file formats, such as Hierarchical Data Format version 5 (HDF5), have been developed to support large, complex, and heterogeneous data. HDF5 uses a "file directory-like structure that allows data to be organized within the file in many different ways, as you might do with files on your computer. The HDF5 format also allows for the embedding of metadata, making it self-describing.

Change management

The introduction of DTs can cause major changes in an organization's goals, processes, and technologies. The purpose of change management is to implement strategies for effecting and controlling change and helping people adapt to it.

Conclusions

Based on an SHM specialist's point of view, this study has used a systems approach to discuss the development of a hard system for the DT of the NH3 fuelling system for the NH3CRAFT project. Relevant issues were discussed by the consortium partners. A decision has to be made on whether or not to develop a DT of the NH3 fuelling system in the future to help maintain its structural integrity.

Ethics and consent

Ethical approval and consent were not required.

Data availability

No data associated with this article.

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Open Peer Review

Current Peer Review Status: ? ?

Version 1

Reviewer Report 09 January 2026

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Arianna Bionda
Polytechnic University of Milan, Milan, Italy

The manuscript presents the development and application of a Digital Twin framework for ammonia (NH_3) bunkering systems, with the aim of supporting safety, operational understanding, and system integration in the context of alternative fuels for maritime applications. The study describes the overall project structure, the main technological components involved, and the intended role of the DT in monitoring and decision support during bunkering operations.
The topic is relevant, as ammonia is increasingly considered a promising non-conventional fuel for decarbonising maritime transport. However, the methodological section of the paper appears underdeveloped, and does not clearly articulate the research framework adopted. In particular, although the authors state that a "systems approach" was applied in the development and assessment of the DT for ammonia bunkering, the paper does not provide a clear definition/scope of what is meant by systems approach, nor does it explain how this approach guided the structure of the study or the analysis of results. The literature reference here introduced appears not sufficient to describe the rationale/framework, making it difficult to assess the methodological robustness of the proposed approach.

More generally, the paper presents the project outcomes primarily as a report of activities performed, rather than as the result of a clearly framed research methodology grounded in prior work. The initial sections would benefit from a stronger connection to the existing research background and to related projects in the field of alternative and non-conventional fuels. While the specific application to ammonia bunkering for vessels is novel, relevant parallels could be drawn with Digital Twin applications and system-level studies involving other alternative fuels (e.g. hydrogen, methanol, LNG), particularly in terms of safety assessment, system integration, and operational risk management.

Major issues to be addressed:
- In introduction, please include examples of DT for system design with particular reference to alternative fuel domains (vessel - automotive - aerospace - trains - industrial sites)
- In method section, (i) provide a clear definition of “systems approach”, supported by references, (ii) explicitly explain how this approach informed the study design and (iii) clarify what

methodological advantages the systems approach + DT provides compared to alternative modelling or simulation strategies
- in the conclusions, (i) include a comparative discussion with other DT or system-based studies, even if they concern different fuels or sectors. Plus, (ii) discuss the transferability of the proposed approach to other non-conventional fuels or maritime applications and (iii) states the limitations of the study.

Is the rationale for developing the new method (or application) clearly explained?
Partly

Is the description of the method technically sound?
No

Are sufficient details provided to allow replication of the method development and its use by others?
Partly

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
No source data required

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: yacht design, naval architecture, hydrogen vessel design, digital technologies for maritime sector

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 31 December 2025

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The topic is timely and the systems framing is useful, but the manuscript currently reads more like

a structured narrative overview than a reproducible “methods” contribution. It needs clearer methodological rigor (how the systems approach was applied), stronger requirements/traceability to decisions, and more NH_3-specific technical depth to support its feasibility conclusions.

- Can the authors state the novelty more explicitly: what is new beyond existing DT/SHM conceptual frameworks—specifically for NH_3 fuelling systems (not ship hull DTs in general)?
- Since Digital Twin (DT) is relatively new in the context of NH_3 fuelling systems, please strengthen the introductory DT background by citing seminal and widely cited DT papers from other established domains (e.g., manufacturing/Industry 4.0, aerospace/PHM, offshore/process industries, energy systems). This will (i) provide an authoritative definition and taxonomy of DT, (ii) clarify key DT building blocks (data–model synchronization, fidelity, bidirectional coupling, V&V), and (iii) justify why the proposed DT architecture is appropriate before narrowing to maritime NH_3-specific challenges.
  (refer 1,2,3)
- (refer 4,5)
- The paper claims to use a “systems approach”; can the authors describe the method steps used to execute it (e.g., stakeholder elicitation protocol, requirement capture, functional decomposition procedure, gap identification criteria), rather than only describing systems concepts?
- Can the authors define one or two concrete use cases (e.g., leak prevention, wall-loss monitoring, fitness-for-service decisions) and show how the proposed DT architecture produces actionable outputs for those use cases?
- Please provide a requirements-to-function traceability: map “key decisions / functional elements” to (i) required inputs, (ii) models/algorithms, (iii) outputs, and (iv) acceptance criteria (what constitutes “good enough” DT performance).
- Sensor strategy: can the authors justify sensor selection and placement for NH_3-specific risks (corrosion under insulation, embrittlement, cracking), and explain how sensor coverage limitations will be handled (e.g., inference for uninstrumented regions)?
- Data fusion is listed as a gap; can the authors propose a specific fusion strategy (levels of fusion, synchronization, uncertainty handling) and identify what “success” looks like (metrics, validation plan)?
- The Asset Information Model (AIM) is central; can the authors specify the data schema (minimum fields, metadata requirements, versioning, provenance) and how AIM will interoperate with SCADA and inspection/point-cloud data?
- For computational and analytical models (FEA, ECA), can the authors clarify the model fidelity strategy (what must be high-fidelity vs simplified), update frequency, and how real-time data will calibrate/condition model states?
- The manuscript mentions LLM-based document search; can the authors add a short discussion on governance and safety (traceable sources, hallucination safeguards, access control) given the safety-critical context?
- Technology gap Table: can the authors explain how gaps were identified and prioritized (risk-based? cost/benefit? TRL/qualification effort?), and include a brief rationale for each recommended action.
- Technology qualification and procedure qualification sections are valuable; can the authors connect them to a practical verification & validation plan (bench tests, mockups, acceptance thresholds, staged milestones)?
- Interfaces are highlighted as a challenge; can the authors propose a standardized data format approach (e.g., HDF5 usage details, naming conventions, metadata embedding) and an integration architecture (edge vs cloud vs hybrid)?

- Cybersecurity is mentioned; can the authors specify a threat model and baseline controls appropriate for a vessel environment (offline modes, segmentation, authentication, logging)?
- The manuscript states “No data associated”; can the authors strengthen credibility by including at least an illustrative example (sample FMEA/RBI outputs, a mock sensor stream + metadata record, or a minimal prototype workflow) even if full project data cannot be shared?
- Please add a clearer limitations paragraph: this is a feasibility/framework paper (not a validated DT implementation), and conclusions should be scoped accordingly.

References

1. https://www.sciencedirect.com/science/article/pii/S1226798825005987.
2. https://www.mdpi.com/2075-5309/15/16/2834.
3. https://www.mdpi.com/2076-3417/15/8/4481.
4. Latif, K., Sharafat, A., Tao, D., Park, S., & Seo, J. (2024). Digital Twin for Excavator-dump Optimization based on Two-stream CNN-LSTM and DES. KSCE Convention Conference and Civil Expo, 17–18.
5. Sharafat, A., Latif, K., Park, S., & Seo, J. (2022). Digital Twin-Driven Optimization of Blast Design for Underground Construction. Proceedings of the KSCE, 1–2.

Is the rationale for developing the new method (or application) clearly explained?

No

Is the description of the method technically sound?

Partly

Are sufficient details provided to allow replication of the method development and its use by others?

Partly

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Digital Twin

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.