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REVIEW

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Challenges when creating a cohesive digital twin ship: a data modelling perspective

Ícaro Aragão Fonseca and Henrique Murilo Gaspar

Department of Ocean Operations and Civil Engineering, Norwegian University of Science and Technology, Ålesund, Norway

ABSTRACT
A digital twin is a digital asset that simulates the behaviours of a physical counterpart. Digital twin ship literature identifies that the concept is already being applied to specialised problems, but no clear guide exists for creating broader interdisciplinary digital twins. Relevant dimensions of product data modelling and previous attempts at standardizing ship data elucidate the requirements for effective data modelling in a digital twin context. Such requirements are placed in a broader perspective for digital twin implementation that encompasses challenges and directions for future development of services, networks, and software. Finally, an open standardization for digital twin data is proposed based on lessons extracted from this panorama, proposing its application to a research vessel.

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digital twin; digital thread; simulation; product data modelling; data standard; open source; internet of things; digitalization

1. Origins, definition and purpose of the digital twin

A focus on digitalization of the maritime industry has been increasing significantly, with new technologies expected to support faster completion of processes and data use during decision-making in the maritime value chain. The concept of digital twin aligns with this overall trend. Boschert and Rosen (2016) trace the origins of the digital twin to the aerospace industry, in which replicas of complex physical systems were commonly constructed, as, for example, during NASA's Apollo space programme or by Airbus with its Iron Bird test rigs. Before system deployment, such replicas can be used to test systems integration and train crew members. During operational phases, engineers can use them to simulate operational alternatives and study issues that appear on a working aircraft by mirroring its behaviour. More recently, advances in simulation methods for engineering are expected to the enable reproduction of these practices using digital simulations, thus conceiving a digital twin system. In the early 2000s appeared the first mentions the possibility of extending product lifecycle management (PLM) platforms with data collected from the physical product in order to mirror it with the virtual counterpart (Grieves and Vickers 2016). At the same time, simulations were already used to support the operation of physical systems, even if with a relatively narrow scope. Cameron et al. (2018) cite some examples in the oil and gas sector which are analogous to a digital twin of a multiphase pipeline in the context of a broader oil and gas installation, or even to the digital twin of a valve, with components including sensors and actuators.

The vision established by NASA in a 2010 draft report (Shafto et al. 2010, p. 18) has greatly influenced the general perception of a digital twin.[1] The report outlines the concept as 'an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.' The report lists vehicle systems modelled by a digital twin and its final role played in supporting mission success. As West and Blackburn (2017) note, the vision of the digital twin described in the report is ambitious, with descriptions of 'ultra-realistic' integrated models that are so detailed that they accurately represent an aircraft's 'manufacturing anomalies,' while remaining suitable to conduct simulations that assist operations continuously. In a later work (West and Blackburn 2018), they argue that while the digital twin concept on such moulds is impractical to implement fully in the following decades, it can still facilitate the more streamlined system sustainment even without achieving a perfect degree of realism.

It is thus critical to identify ways the concept can prosper, even considering its limitations, with the intention of reaping some expected benefits. The first step is recognizing that despite its grandiosity, the digital twin concept revolves around a central principle –

CONTACT Ícaro Aragão Fonseca icaro.a.fonseca@ntnu.no

[1]The Defense Acquisition University (DAU) glossary (2020) from the United States Department of Defense (DoD) defines a digital twin similarly, with the addition that it should not only mirror asset behaviors but predict them.

mirroring and assessing a physical asset's constitution and behaviours using a simulated counterpart. This principle is reflected in the four expected use cases of the digital twin specified in the NASA report – simulate a mission before it is executed, mirror the behaviours of its physical twin during operations, perform in-situ forensics of a potentially catastrophic fault or damage, and serve as a platform for studying the effects of modifications in mission parameters that were not considered during design. These use cases are similar to the physical system replicas discussed previously; they share the purpose of supporting decision-making during operations, either in (near) real-time or preemptively. The digital twin represents a tool for verification and validation of system behaviours, and the study and debugging of operational problems. After the aerospace sector put the digital twin forward, it has been adopted by an array of other industries. This process has been aided by developments in industrial Internet of Things (IoT), sensor technology and miniaturization, which contribute to obtain and store measurements as digital data (Figure 1).

2. Examples of digital twin ship initiatives

With the popularization of digital twins, the first applications to the ship domain have started to appear. Digital twin ship implementations found in the literature accord with the potential applications discussed above, and they can be generally clustered into two main groups. The first is decision support for ship operations, with a focus on condition monitoring and calibration of simulation models based on real operational data. Coraddu et al. (2019) estimate speed loss caused by marine fouling using a simulation model based on a neural network; the network receives data measured from a vessel and returns an estimate of speed loss. The tools demonstrated superior performance in comparison to the ISO standard for estimating fouling. Given this method based on machine learning, the proposed model requires considerable amounts of data.

Schirmann et al. (2019) present a digital twin for ship motion and estimation of structural fatigue due to wave response. Given weather forecast data for a given route, the digital twin estimates expected cumulative damage the ship would endure. Different from the previous example, the authors used specialised formulas, not machine learning, to simulate ship behaviours. Danielsen-Haces (2018) apply a digital twin to autonomous vessels, in this case, a ship model built for research. The digital twin has two use cases – condition monitoring and calibration of the propulsion system simulation models based on operational data. Bekker (2018a) details plans to implement a digital twin of a polar supply and research vessel, based on a comprehensive sensor infrastructure installed previously on the vessel. Figure 2 shows that the plan covers aspects from context, such as waves and ice, and from ship states, such as a rigid body and structural responses to waves, and the effects of motion on human factors. Sensor readings will be processed using data analysis techniques such as machine learning, with initial applications already yielding positive results (Bekker et al. 2018b).

The second group includes digital twins used as tools for system integration testing and personnel training. Tofte et al. (2019) describe a system for emulation of control systems, in which a detailed simulation model of the lay tower clamp in a pipe-laying vessel is linked to controllers to include hardware and a human in the loop system, which can be used for hardware testing and operation training. Dufour et al. (2018) also discuss applications of a digital twin for system integration testing of naval ship power systems with hardware in the loop.

3. Digital twin ship content and usage

3.1. Digital twin data

Given the systemic complexity of vessels, it is natural that most current digital twin implementations do not yet include overarching, integrated digital twins; they are usually in early stages of development or were created to address specific problems. Similarly, commercial solutions from software vendors are

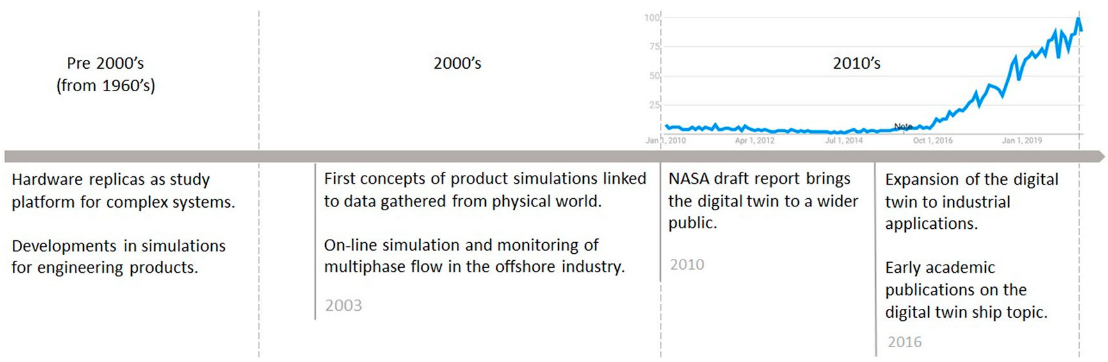

Figure 1. Timeline of development of the term 'digital twin' – the term as we know appeared in the last decade, depicted by the chart with the normalized quantity of Google searches on the top right.

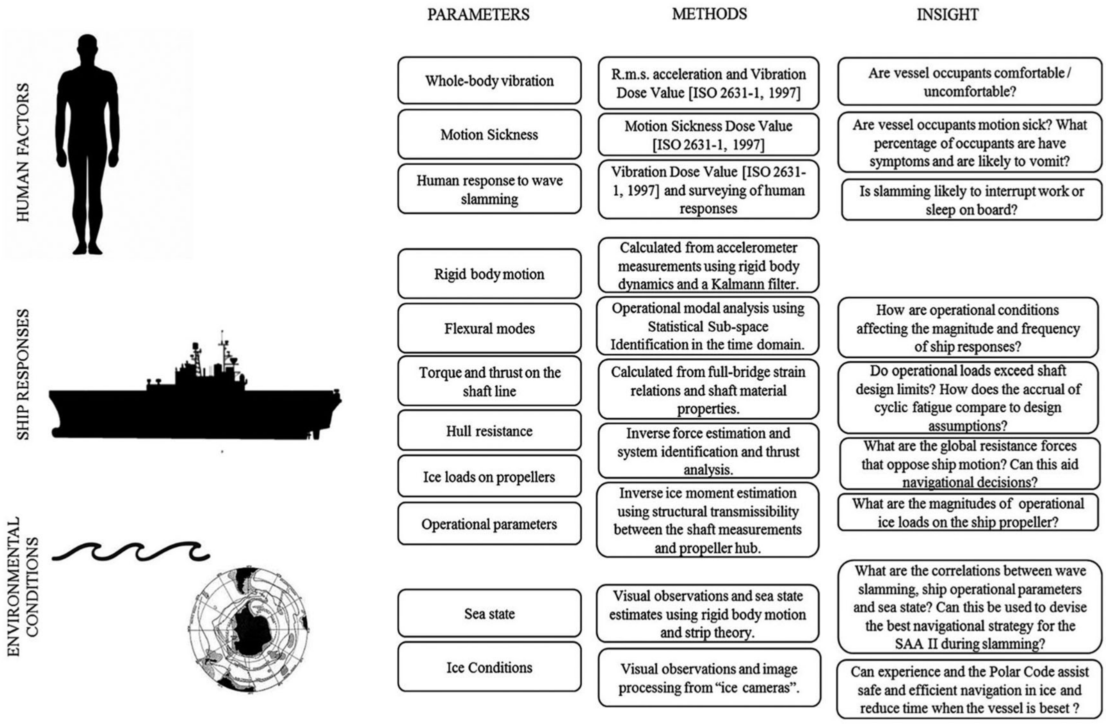

Figure 2. Measured parameters, analysis methods and expected insights for the proposed digital twin by Bekker et al. (2018b).

comprehensive ship representations, but functionalities for monitoring and simulation of ship behaviours during operation are comparatively new. Attempts to characterise the data content of digital twins usually converge on a typology based on three constituents – asset representation, behavioural models, and measured data (Cabos 2018; Cameron et al. 2018). The last category can be broken down into data measured from the asset itself and that from its operational context (Erikstad 2017). Figure 3 illustrates how this data interacts to realise different digital services, with the digital twin working as a central hub giving access them. The collected data must align closely to interact efficiently, and thus the exact contents of a service implementation depends on its domain.

The production and use of data in each of those groups occur differently throughout an asset's lifecycle. Simulation models that define an asset's constitution and behaviours also define permanent aspects of the asset, and states and environmental contexts are much more transitory because they are perceived in real-time during operation as data are gathered from sensors and other perceptual devices. Given that distinction, models of assets and behaviours should be reused from previous lifecycle stages, thus establishing a digital thread of data use over the product's life.

3.2. Asset representation

A ship's representation commonly revolves around a 3D model, which can be assembled by aggregating several CAD files generated during the ship's design, such as the hull, structure, and outfitting modelled by designers, complemented by machinery and component models acquired from third parties. A digital twin might also include 3D models of these elements

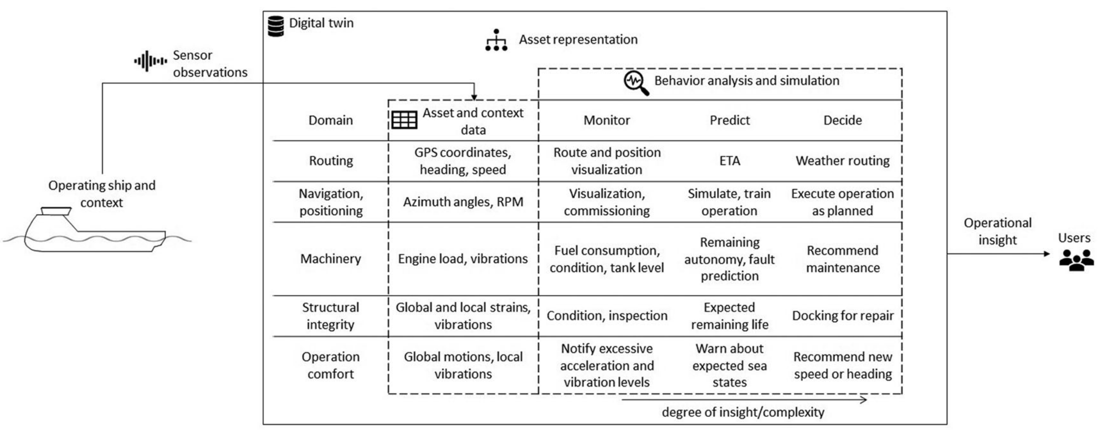

Figure 3. Digital twin elements and usage in the implementation of services in various domains.

stored as lightweight visualization formats that are adequate for rendering animations. To complete the physical representation, a 3D model must be complemented with metadata that describes weight distributions and material characteristics. The same metadata structure can be used to organise component descriptions, maintenance comments, and other accessory information.

3.3. Behaviour models

The behaviour model establishes a bridge between a digital asset representation and the physical reality measured as data. This bridging occurs in ways that depend on the purpose of the digital twin; a simulation can feed directly from sensor log streams to provide real-time support, or it can rely on static (i.e. stored) data to analyse current asset conditions and performance on previously executed operations. Such models might employ various methods to achieve these goals, whether based on physics or statistics, including signal processing and machine learning (Erikstad 2018). Erikstad (2017) presents a progression from behaviour modelling, as commonly used in engineering design analysis, to operation support, as proposed by the digital twin, emphasising the importance of sensor input in distinguishing typical engineering analyses and simulations from a digital twin. Thus, context and behaviour in the digital twin are not only modelled but measured to obtain insights about a ship's operating performance. This means that if such behavioural models are to be reused throughout the product's lifecycle, some changes to the current engineering design methods might be necessary. Simulation models created during design must be conceived to not only analyse the product's behaviour under prescribed conditions but support its operation with services such as validation of the designed product and forecasting of various operational situations. This ultimately creates the potential to analyse operational data to aid design decisions of new vessels, thus closing the loop of data use during the lifecycle.

3.4. Measured data

Data describe an asset's state in its operating context, which can be accomplished using sensor logs, reports that describe its physical condition, and other data. With advances in connected devices and remote monitoring technology, the novel value introduced by a digital twin will be extracting insights from sensor data rather than being an archival system for written reports. To ensure that a digital twin realises that value, considering a few issues when planning an effective sensor setup is required. When mirroring the asset's operating state, it is important to acknowledge factors regarding its context that influence measured behaviours. One important concept is the distinction between raw and net data. Not all sensor logs, or raw data, will be immediately useful for a digital twin, so it might be necessary to perform post-processing to extract physical meaning from it (i.e. the net data). For example, consider a digital twin designed to measure the motion response of a vessel that is operating near an oil platform. The setup must measure not only vessel motion, but wave characteristics in its geographic context. If the wave is measured using a buoy, it is necessary to employ algorithms that extract period and significant wave heights from buoy elevation measurements. Similarly, it might be necessary to decompose readings of the motion sensors installed on the vessel into motion components on six degrees of freedom. These implications highlight the importance of purposeful state measuring on digital services, which we discuss later.

4. Approaches to handling of ship data

4.1. Data modelling and usage in the ship industry

Traditionally, digital management of a ship's lifecycle relies on many specialised software tools that produce discrete solutions to their respective problems, rarely influenced by interoperability. Several factors lead to this scenario, some of which are common to other engineering domains. One example is the perception of proprietary data formats as a competitive advantage by adversarial software providers (Rachuri et al. 2008). Other factors are specific to the ship industry. In comparison to other engineering disciplines, the ship industry represents a small segment of potential computer-aided design (CAD) customers, an obstacle to justification of big investments in software development (Gaspar 2019). Since the ship industry usually focuses on individual production, its data management is commonly based on tenders, each of which in turn is complemented by an entire framework of choices and variables that influence a vessel's characteristics, and thus its digital representation, throughout the lifecycle. Ship data is, therefore, not necessarily organised systematically, and even less so when the organization is compared among ships, design offices, and yards (Gaspar 2018). Although discussed particularly in the context of ship design up to commissioning, this variability extends to subsequent operational stages, i.e. the domain of interest for a digital twin.

In the absence of an established ship model standard in the industry, alternatives for modelling product data are few and niche, examples of which include some formats and libraries for CAD and 3D visualization (e.g. IGES, STEP, and JT). Gaspar (2019) describes the current scenario of ship software integration as consisting of two trends – suites of PDM and PLM systems by major software providers that offer tools for a ship's lifecycle and specialised tools that allow more flexible connections with such suites. The following sections discuss some extant approaches proposed to model ship data, which are mentioned as a reference point for subsequent examination of how a multidisciplinary digital twin can be modelled and developed.

4.2. Principles of product data modelling applied to digital twins

We begin by comparing the digital twin asset representation to a typical characterization of product model during design. van den Hamer and Lepoeter (1996) decompose the problem of managing product data into five dimensions – views and hierarchy of the designed system, version and status of design data, and variants of the designed product (Figure 4). The tender-based characteristic of the ship industry drastically reduces the importance of the variants dimension; presenting a set of designs as a product family is too preliminary to displace the practice of managing ship data individually. Other dimensions might play a role during a ship's design stage, but they are less relevant in the context of the digital twin. Versioning, for example, accounts for the modification and evolution of design information. Since a digital twin models the asset representation as consolidated after the building stage, it does not need to accommodate multiple versions of the product model. At most, the dimension plays a role in archiving instrumentation logs and other documents collected during operation. The status version tracks validity and consistency of information, identifying valid and superseded versions and controlling change propagation across the digital model. Since the necessity of tracking validity of the digital twin data itself is small or absent, eventual use of the dimension will be to describe the physical status of the asset (i.e. indicating that a component is functioning as expected or that it requires maintenance).

The two other dimensions, views and hierarchy, are central to a ship's lifecycle generally and to the digital twin specifically. Given their importance, they represent recurring themes in the literature, also appearing under the name taxonomies (Otto et al. 2016; Låg and With 2017; Gaspar 2018). This term is used to describe both the various perspectives of a ship and the hierarchical breakdown that organises the data under that view. For example, Siemens presents a 4th generation design (4GD) approach in its PLM package for shipbuilding (Siemens PLM Software 2013; Levisauskaite 2016) that promises to manage design elements independently using a flat structure. A design element contains the global position, CAD geometry, and the lifecycle data of a part, with which a user is able to filter sets of design elements according to rules, for example, by system, location, or attribute. Siemens argued that due to these characteristics, the 4GD approach is able to handle multiple taxonomies without duplication of data, reduce required storage space for files, and provide better support to concurrent modification of parts.

4.3. The SFI group and classification system

One example of an early and successful taxonomy for organization of ship data is the SFI group and classification system, which today is licensed commercially by SpecTec (Xantic 2001). The system was developed as a response to the challenges of exchanging data consistently inside and among organizations. As electronic data-processing technologies were introduced in the industry, corporate players searched for a standardised

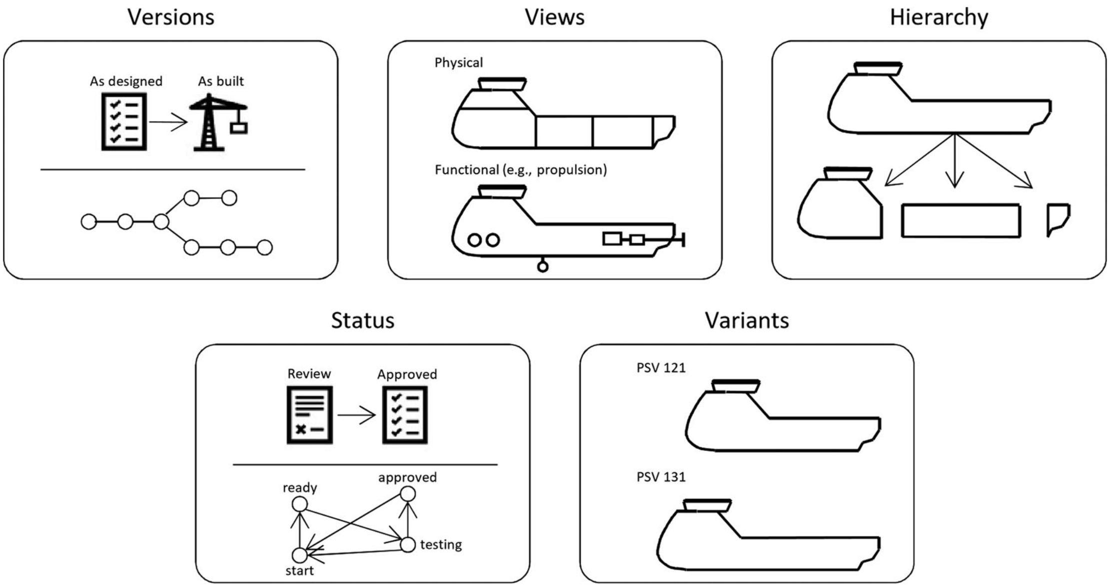

Figure 4. Product data management decomposed into five dimensions – versions, views, hierarchy, status, and variants. Adapted from van den Hamer and Lepoeter (van den Hamer and Lepoeter 1996).

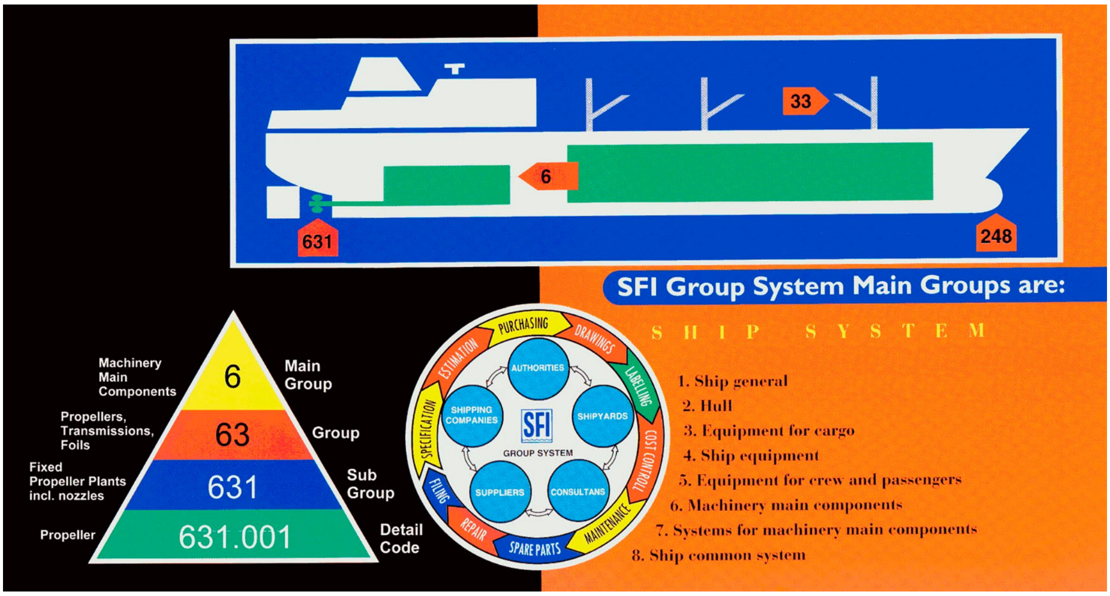

Figure 5. SFI summary with use cases, main groups in the hierarchical system, and an example of a tag system applied to a propeller component (Xantic 2001).

solution for data handling that could be adapted to yards and ships and that was understandable to humans (Manchinu and McConnell 1977). Development was conducted by a consortium of private shipyards and the Ship Research Institute of Norway, currently SINTEF. The first tests were performed using the system as an on-board maintenance code for types of ships, a system released in 1972. Its use cases centred on indexing and identification of drawings and specifications, and control and accounting of parts, work, and materials (Figure 5). The SFI group system is based on a hierarchical, numeric tag system that is guided by a strictly functional view of the ship that indexes components not by system, but by groups according to component function. The numeric tag system consists of three levels that are supplemented by a detail code for individual components and materials. This hierarchy is mapped to the indexed information, including drawings, specifications, and accounting registers for material and labour.

4.4. Standard for the exchange of product model data

Another standardised approach to ship product model data is the ISO 10303 standard, informally known as STEP (Standard for the Exchange of Product Model Data). Whitfield et al. (Whitfield et al. 2003) conducted a literature review on the topic of ship product modelling, identifying STEP as the most significant development by far in that area. By standardizing data for exchange among software systems, especially pre-commissioning phases of the lifecycle, STEP was expected to establish the basis required for an ecosystem of heterogeneous tools to flourish. Development began in 1984, and the standard was released a decade later. In the following years, five application protocols (APs) were released specifically for ship data, covering arrangements, moulded forms, piping, structures, and mechanical systems (Figure 6[2]). One AP included an application activity model that described the intended process for where the standard would be used, an application reference model that described information requirements, and an application-interpreted model that described schema with which the modelled data should comply. The schema was based on entity types, which are analogue to objects in object-oriented systems, that use concepts such as property and inheritance.

In practice, STEP's adoption was rare in the shipbuilding and other industries, falling short of its original purpose of becoming a de-facto standard. Gielingh (2008) noted that STEP had its use limited to the exchange of 3D CAD models, clustering the reasons for low adoption into three groups – business models, legal aspects, and industrial readiness. One obstacle was that competing software providers lacked interest in complying with standards, due in part to an asymmetry in which vendors that invested in standard compliance would not reap the benefits of such compliance. Besides reasons for low adoption, research reported poor technical performance of the standards that occurred due to differences in CAD representations, information scope, and entity-oriented schema. These differences increased the change of information losses when exchanging data among applications. For example, attempting to enable data

[2]Figure 6. Diagram of STEP standards and Figure 8. Possible inputs and services of a shipboard data server are reproduced by Ícaro A. Fonseca in Challenges when Creating a Cohesive Digital Twin Ship: A Data Modelling Perspective under licence from Standard Online AS July 2020.

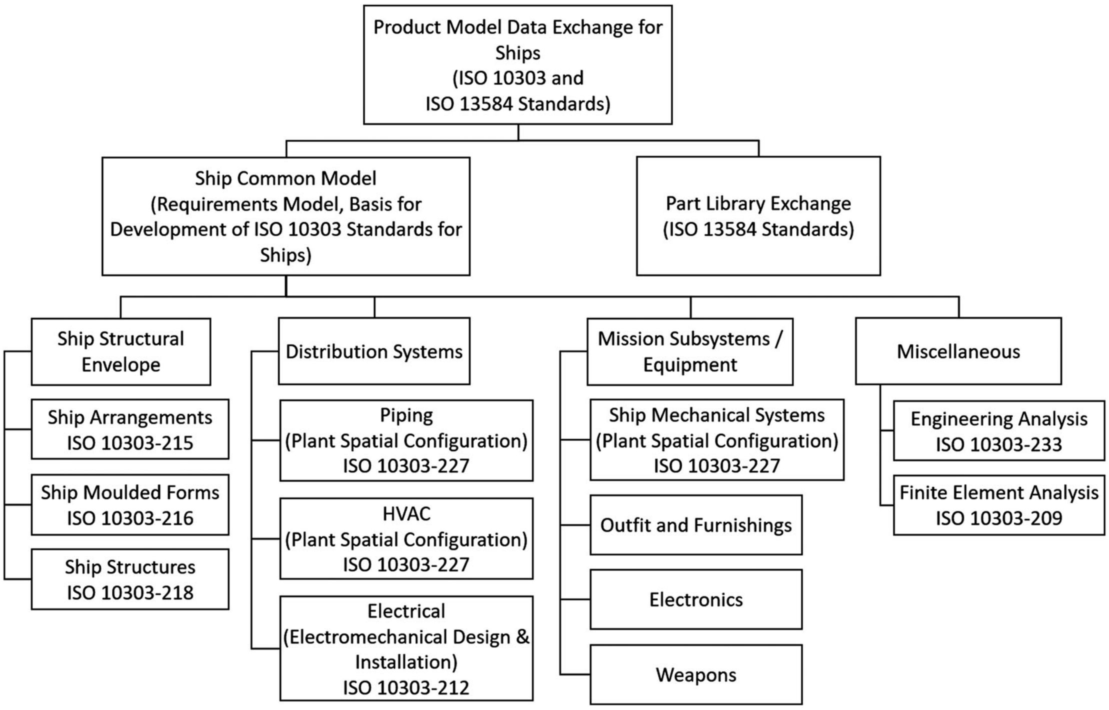

Figure 6. Diagram of STEP standards applicable to the ship product model according to ISO (ISO 2004). The APs include both specialised standards for ships and general standards that can be applied to that domain.

exchange among multiple ship design programmes, Whitfield et al. (2011) chose a custom neutral model instead of STEP after identifying that the latter would disallow a complete exchange of digital content among extant software.

In retrospect, business factors appear to have had great influence over the success of product data technologies. Consider construction, another tender-based sector that delivers large, complex systems. Industry Foundation Classes standards, the basis for building information modelling (BIM), have been gaining significant adoption in the industry, allowing interoperability among software packages. From a technical viewpoint, IFC shares many similarities with STEP, also relying on entity-oriented schema. IFC standards even include elements of STEP in its composition, such as some APs and the information modelling language EXPRESS, which is commonly perceived as complicated and technically limited (Whitfield et al. 2011; Cameron et al. 2018). From a business viewpoint, development of IFC was vendor-driven more than STEP was (Gielingh 2008), and adoption of IFC has been aided by the public sector in some European countries, which now require compliance with IFC from companies bidding to participate in the construction of public projects.

5. Towards a cohesive digital twin ship

5.1. A broader picture

The comparison between standardization approaches in the previous section leads us to argue that models for ship data must be supported by matching business models and must be motivated by parties interested in implementing them. In the case of a digital twin ship, these challenges are compounded by the presence of multiple stakeholders (e.g. component suppliers, yards, and ship operators) and new requirements when using the digital model to interact with sensor streams gathered from operation in real-time. Figure 7 organises these concerns into three layers, from a higher service and business level, downstreaming to network infrastructure, and finally to software. Each of these layers influences the chances of establishing a successful, cohesive digital twin based on standardised data models that can be reused across tools. The following sections discuss not only challenges that each layer imposes, but directions for overcoming them found in the literature regarding digital twins and digital services generally.

5.2. Services and business

Regarding specific digital twin purposes, the possibilities of applying digital twin principles to operational problems have not yet been identified exhaustively. A great breadth of potential domains and approaches exist that are being gradually matched to supporting business models as these are discovered, tested, and operationalised. Nokkala et al. discuss problems with data governance in an environment of shared data use using a case study in which the authors interviewed employees of a shipyard and its collaborative network (2019). They found that despite that the interviewees

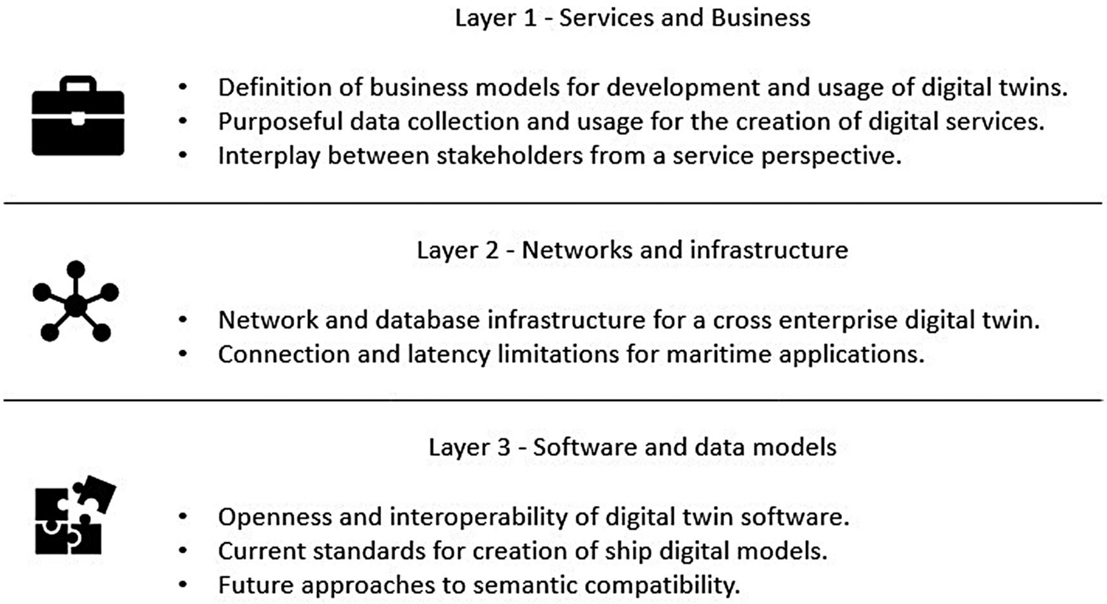

Figure 7. A division of challenges for implementation of a cohesive digital twin ship from higher to lower levels (layer 1–3, respectively).

recognised the potential business value of data use easily, there was strain between the necessity of defining a clear business model and the necessity of conducting exploration to identify ways in which the data could used. The interviewees mentioned the large amounts of data that are collected and stored by default during operation, even if without a clear business case; data are collected and stored 'just in case.' Erikstad (2019) corroborates this phenomenon, which is characterised by the contradiction that although there are large amounts of operational data available from sensors and instruments, there is not a clear use for them. As a result, development and implementation of many existing sensor-driven services have been opportunity – rather than needs – driven, and thus the author calls for purposeful design of digital services in which user needs regarding decision support for operations are traced to specific sensors installed on the vessel. Resolving these challenges might pass through creation of innovative business models among stakeholders, one of which could be shipbuilders transitioning to service providers that offer information and support to a ship and its digital twin after delivery (Van Os 2018). Morais and Goulanian (2019) offer the case of Ulstein, which started to provide solutions for integration among control, power management, and energy management systems for the vessels it builds.

5.3. Networks and infrastructure

Besides higher-level concerns regarding business models, the interplay among stakeholders will also move downstream to network infrastructures for data-sharing among parties. Bole et al. (2017) discuss that in such contexts, delivery of documents from the shipbuilder, the party that builds and integrates the vessel as a system, to the shipowner will evolve from being a formality to a crucial step during implementation of a digital twin system.

Given the niche aspect of digitalization in the maritime industry when viewed from a broader industrial perspective, it may be a wise strategy to adapt solutions from broader domains to the maritime context in order to reap benefits from adoption, support, and future developments. Rødseth and Berre (2018) propose Maritime Data Space (MDS) as an enabler of a vision of a digital twin linking databases from various stakeholders. MDS is an extension of the Industrial Data Space (IDS) framework developed by the Fraunhofer research organization with the goal of facilitating exchange of data in business ecosystems by using standards and common governance models (Otto et al. 2016). The IDS framework suggests a decentralised approach to data storage, while allowing parties to determine conditions for access to the data they own. IDS aims to assimilate platforms and services by establishing an app store and an open, neutral approach in which decisions are made jointly by the research team and users.

Another relevant initiative in that domain is the recently published ISO 19847 'Shipboard data servers to share field data at sea' (ISO 2018a). The document specifies requirements for servers collecting and sharing data from shipboard systems, which can be streamed to services such as condition monitoring, performance analysis and weather routing (Figure 8). The standard also describes concepts for the communication between the shipboard server and an onshore server for long-term data storage.

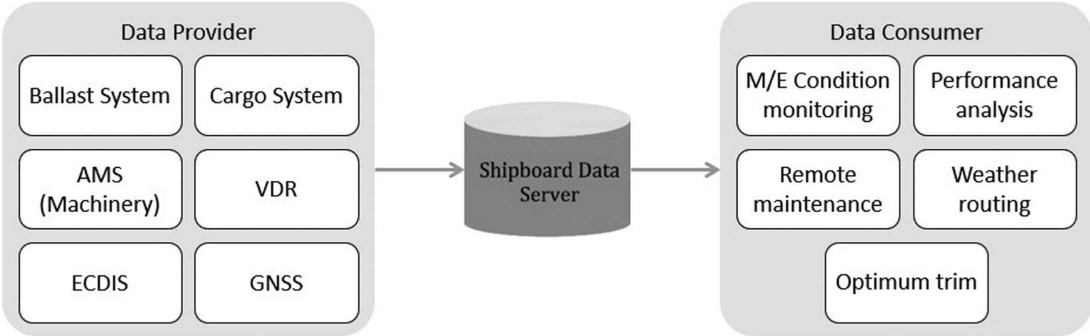

Figure 8. Possible inputs and services of a shipboard data server according to ISO 19847 (ISO 2018a).

Both the initiatives mentioned above take measures to deal with the peculiarities of ship operation such as system complexity and limited connectivity. Regarding the last point, Datta (2017) recommends that edge data processing could be prioritised in order to ease demands for latency and frequency of package delivery.

5.4. Software and data models

Recent advances in interoperability correspond with lessons learned from previous ship modelling. One example is the continuous rise in the perception of the importance of interoperability among digital systems, to a point at which even providers of proprietary solutions claim esteem for format and platform openness. Stachowski and Kjeilen (2019) discuss two CAD formats as examples of Siemens' willingness to promote openness – JT, which has become an ISO standard, and Parasolid, which is licensed to other companies and has had significant adoption. DNV GL (Sharma et al. 2017) present a preliminary project for digital twin platforms, Nauticus Twinity, as an open collaboration platform. Morais and Waldie (2018) emphasise the importance of approaches that allow interconnection of digital platforms such as open architectures, software modularization, and development of application programming interfaces (APIs).

Rachuri et al. (2008) classify PLM standards into four major types – type zero for implementation languages, type one for information modelling, type two for content standards, which can be further divided into sub-classifications, and type three for standards of architectural frameworks. Web-based solutions have been gaining popularity in engineering software such that HTML and JavaScript represent some of the most important type-zero standards currently in use. Stachowski and Kjeilen (2019) state the importance of Web technologies in the Siemens suite of PLM software. Bole et al. (2017) reported that AVEVA's digital twin technology is predominantly browser-based, and Schroeder et al. (2016) proposed a Web-based digital-twin architecture for monitoring offshore oil and gas platforms, including augmented reality visualization of the system. The advantages of Web services during development of digital twins include platform independence, compatibility with an array of devices and operational systems, preclusion of installation processes, and ease of deploying updated experiences to distributed users.

Regarding type-one standards, XML has been the traditional choice in maritime, but given the recent rise of importance of Web-based solutions, JavaScript Object Notation (JSON) offers a lightweight alternative for data exchange, better human readability, which allows users to interpret data and reduces the knowledge barrier for data manipulation, and broad support in the information technology industry. Adoption of type-zero standards ensures compatibility of software applications on executing devices, and type-one standards ensure that disparate software applications can parse the same information schema. To enable interoperability among applications, it is necessary to establish standards for the information content to be modelled, which means type-two standards. A modern example of a type-two standard is ISO 19848 'Standard for shipboard machinery and equipment data' (ISO 2018b). It was developed in companion with the ISO 19847 and describes sensor metadata such as variable type, unit of measurement, and update frequency both in JSON and XML schema. In the Norwegian maritime context, an continuing research consortium aims to apply the functional mock-up interface (FMI) to enable co-simulation among behavioural models of ship subsystems (Skjong et al. 2017; Hatledal et al. 2020).

Establishing further type-two standardization remains a challenge, but provision of APIs might lower the stakes of overcoming it. Such interfacing approaches might be the most feasible implementation alternative in the short- to medium-term, but they represent a compromise because they do not ensure interoperability among systems per se, but among their interfaces. The most ambitious solutions to this problem suggest transcendence of standardization from something modelled passively to something capable of adaption to enable communication between systems actively. Gielingh (2008) argued that given the burden of establishing common ontology templates for standardization of product data, it is desirable to search for templates that can explain themselves, rather than requiring systems to understand them. Similarly, given the tendency of information technology to evolve faster than standardization consortia are able to keep up with it, the author comments that it would be desirable that such standards provide dynamic features for updating. Datta (2017, pp. 23–24) argued that the difficulty in achieving communication among systems on a semantic level needs to be resolved on a higher cognitive level, where software can 'understand what needs to be understood' (e.g. assembling required communication APIs automatically) and hardware 'senses what needs sensing,' automatically activating and using relevant sensors to address the current problem.

6. Digital twin ship data standardization

6.1. Open digital twin platforms

Challenges identified in previous sections call for standards to enable systematic creation of digital twins that are suitable to modern data infrastructure and that attend to business and service requirements. As in extant Web services, a neutral core data standard for digital twins could represent the basis for an ecosystem of heterogeneous tools, allowing choices among various platforms and connection to external services and applications. This section outlines an approach to such a standard, focusing on the importance of selecting data views and hierarchies that align with the digital twin purpose. The standard provides a mapping between taxonomies and data content in a manner that facilitates understanding and use by humans and computer systems alike. So far, the proposed approach has been applied to a few simplified case studies, including a digital twin experiment performed with a platform supply vessel (PSV) scale model (Fonseca and Gaspar 2020). The digital twin was able to successfully monitor and control the scale model operation, accounting for motion response, navigation, and station keeping on waves. Future research aims to apply the standard to the digital twin of the NTNU's research vessel Gunnerus, as proposed in the following paragraphs.

6.2. Integration of digital twin data

Given the complexity of vessels as systems, it is difficult for single stakeholders, such as shipbuilding companies, to develop an associated digital twin on their own. To distribute the task among various ship stakeholders, digital twins must be created according to standards that enable serialization and exchange among users across companies, allowing yards to integrate such models on an overarching digital twin ship at the same rate at which they integrate the physical subsystems of the real asset. Suppliers are thus able to provide a new feature with the asset, which could, in turn, be commercialised with multiple clients. The integrating party manages an overarching data structure that collects data that are consolidated from the ship design and construction, gradually filling it with component data sent by suppliers and following a top-down approach (Figure 9). The proposed standardization models digital twin elements using repeated objects associated with individual tags for identification of assets, analyses, and data. These elements can be mapped to hierarchies that represent disparate views of data content where systems and SFI establish alternative hierarchies that map data contained in the three other objects.

The asset representation for the digital twin accounts for the ship structure and its physical systems, with data pointing to relevant CAD and visualization files, listing position coordinates and weight data. The digital twin maintainer should aggregate the information necessary to carry simulations that require a holistic view of the asset; and analyses performed during design can also be archived for subsequent use during simulation. For example, results of motion response analyses on relevant loading conditions can be stored in a separate JSON file containing the response amplitude operators (RAOs) for various waves. The file is listed as an analysis under an identification tag and can later be validated with operational data or used to create dashboards simulating an operation to be performed (Miquel et al. 2020). The last component, measured data, is collected from sensor streams and archived for subsequent use. The data are stored according to the ISO 19848 standard, which specifies two types of packages: one describing sensor configuration and other with log readings. In the digital twin, the packages are grouped according to their originating system, and a single sensor system may stream several channels with measurements of different quantities.

The digital twin integration is responsible for organizing individual elements from various suppliers into a meaningful data structure. The digital twin view is primarily system – and operation oriented, so it must be supported by a corresponding hierarchy that organises elements into systems, so the digital twin can close the loop between operational performance and designed functionality. Two taxonomies are suggested on ISO 19848: one by the Japan Ship Machinery and Equipment Association (JSMEA-MAC) and the Vessel Information Systems by DNV GL (DNVGL-VIS). The selected taxonomy is used as a schema to navigate digital twin data by referring to elements' unique identification tags for assets, analyses, and sensors. As observed in the flowchart, it is possible to include multiple hierarchies to arrange the data according to the current task. Besides a system-oriented taxonomy, the SFI group

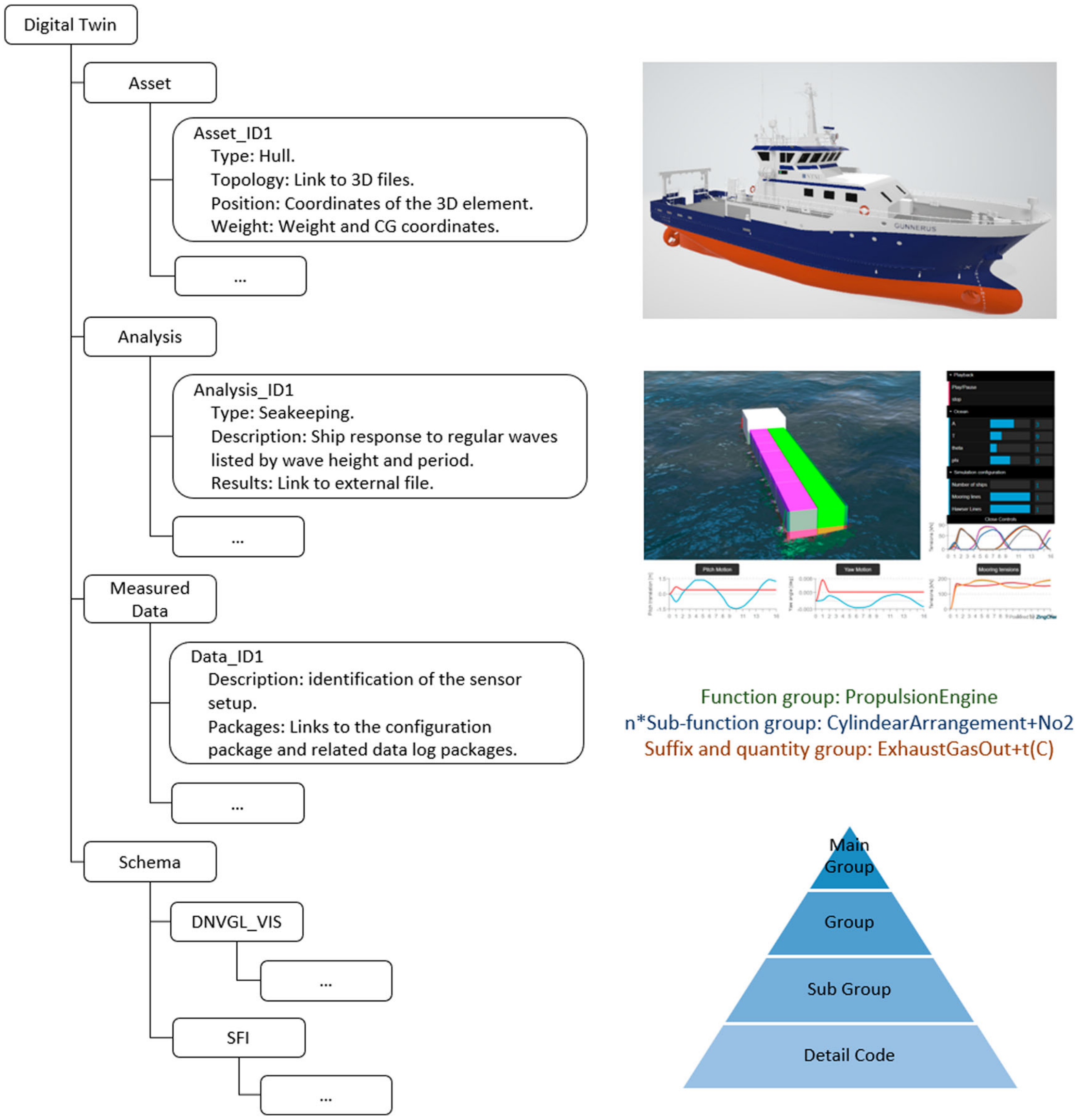

Figure 9. Overall digital twin schema with illustrations of asset visualization, motion simulation dashboard and taxonomies for data organization.

system for shipbuilding can be incorporated in the same manner, and both can be handled independently.

6.3. Digital twin components

In this business scenario, suppliers sell not only the physical subsystems to be installed in the vessel to shipyards, but also an accompanying digital model for integration in the digital twin ship. Data exchanged are serialised into a package with digital twin contents, metadata, and documentation so that use by a receiving party is straightforward. An example of a propulsion system, with dynamic positioning functionality, is detailed in Figure 10.

Asset representation comprises three elements – one bow thruster and two azimuth assemblies with casing and propellers. When linked to operational data, they can be used to visualise the operating propulsion with rotations per minute and azimuth direction. The GL transmission format (glTF) is being assessed as an alternative to serialization and exchange of visualization models of this type. The format allows storage of entire 3D scenes as binary or JSON files, which can be used to transmit geometric models as articulated assemblies that would simplify inclusion on a digital twin visualization.

We previously mentioned approaching standardization of digital twin behavioural models using a bottom-up perspective, which means that if separate component manufacturers adhere to standardised interfaces that allow communication of simulated models, it is possible to include these on the exchange package for aggregation to the overall digital twin ship. The FMI standard provides that type of functionality by allowing the user to create functional mock-up units (FMUs) that can be compiled and exchanged as binary files. Those units can be prepared for co-simulation, encapsulating also the necessary solvers, or as model-exchange units, which rely on external solvers for execution. The supplier would provide additional

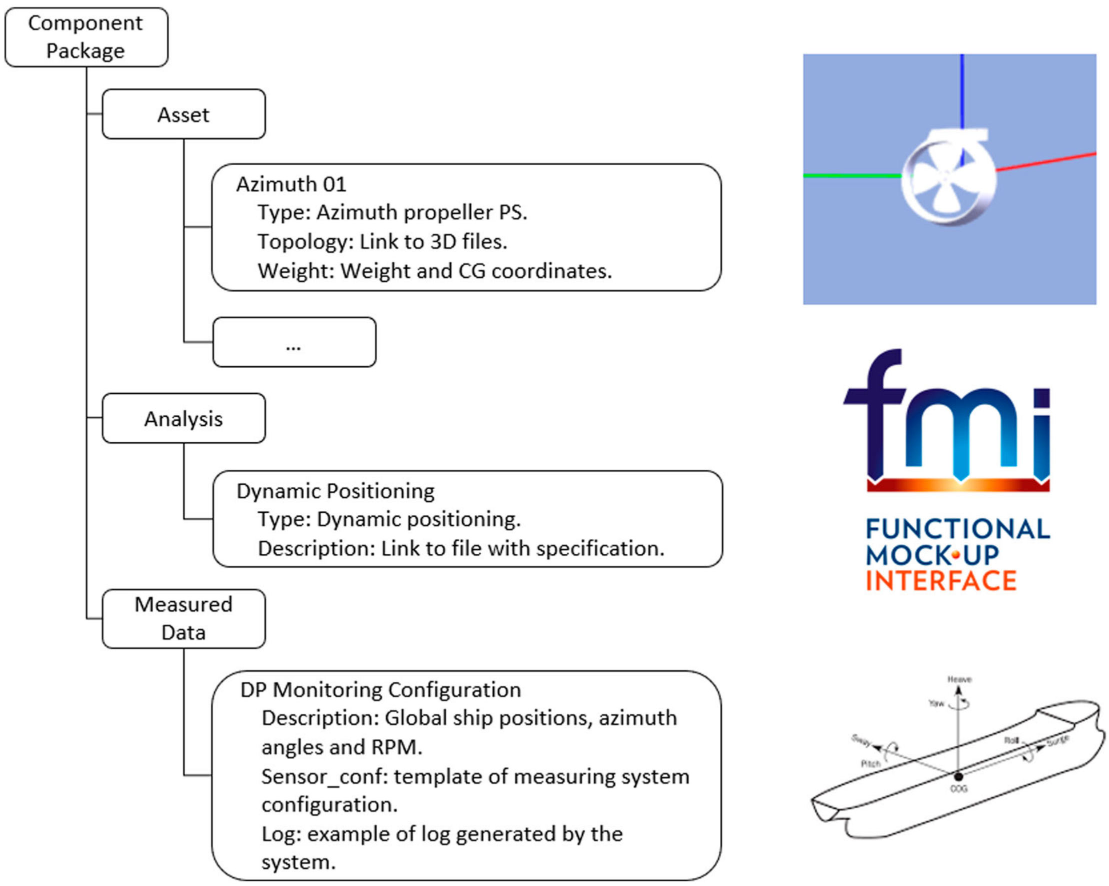

Figure 10. Component schema for serialization and exchange of packages among stakeholders.

documentation describing a recommended instrumentation setup for the physical system and explaining how data gathered from that setup can be linked to visualization and behavioural models. Another approach is to provide the analysis as a self-contained system, with API documentation specifying inputs and outputs. The system is linked to a sensor setup and communication occurs only through the exchange of input commands and output logs that measure the system behaviours of interest. The logs link with the digital twin visualization and are later stored in the digital twin database. That alternative might give more freedom to the supplier, but it requires the effort of developing and maintaining the complete simulation without the basis provided by a neutral standard.

7. Conclusion

The creation of a cohesive digital twin ship faces various challenges, not least the tradition of siloed software systems and data handling in the maritime sector. In the same way that web-based approaches have contributed to compatibility regarding device support and data parsing, the adoption of open standards for engineering models may enable advances in use and exchange of digital twin content. The last years have seen progress in that direction with the appearance of open standards aimed specifically towards those purposes, but further work is necessary. To achieve success, it is necessary that actors in the ship value chain are willing to adopt a collaborative approach to data handling. With this mindset, they can recognize the opportunities of getting involved with standardization initiatives as means to shaping future digital services and research according to their desires and necessities.

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ORCID

Ícaro Aragão Fonseca http://orcid.org/0000-0003-0189-2576
Henrique Murilo Gaspar http://orcid.org/0000-0003-2128-2863

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