Proceedings of 15th International Marine Design Conference (IMDC-2024)
June 2-6, 2024
Amsterdam, the Netherlands

Data Models in Ship Design and Construction - Insights from 4D BIM

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ABSTRACT

The lack of a cohesive understanding of a ship product data model, from design to operations, is currently a limiting factor in realizing more efficient ship lifecycle management and design processes. The paper sheds light on the history and gaps in realizing an integrated, interoperable, and multi-domain ship product data model. It also explores practices from BIM (Building Information Modelling) as an inspiration for solutions to overcome challenges related to information modeling, integrated design environment, and 4D engineering and planning.

KEY WORDS

Ship product data model, Building Information Management (BIM), Lifecycle Management

THE IMPORTANCE OF COHESIVE PRODUCT DATA MODEL

Accurately representing a product's data across its lifecycle is a challenge most industries face today. For engineer-to-order (ETO) sectors that handle the design and production (or construction) of multi-functional assets, such as manufacturing, construction, and shipbuilding, competitiveness depends on how well the product data is maintained physically and digitally (Wyman et al., 1997). Proper management enables process and operational efficiency and decreases the likelihood of technical errors that become more expensive to reconcile as the product matures (Rigterink, 2014).

Today, various international standards provide an understanding of how the data of multi-functional assets can be represented appropriately and communicated across highly dispersed teams via a product data model (ISO, 2022; DNV AS, 2023; ISO, 2004b, 2024). A product data model is a way to organize or structure relevant product data. Other terms equivalent to this concept are Common Reference Information Models (RIM) (ISO, 2022) or Asset Information Models (AIM), which are a 'collated set of information gathered from multiple sources' encompassing the structure and relationships of the data in these sources and or databases (DNV AS, 2023). Where there is no cohesive product data model, companies risk lacking the capacity for (1) efficient product lifecycle management (PLM) and (2) challenges in the integration and interoperability of asset data (Wyman et al., 1997).

The shipbuilding industry currently does not have a standard solution to tackle these gaps, as a complete view of a ship's data (from design to operations) has yet to be realized. A ship is a complex system, and both the built physical asset and digital representations of a ship are often developed in a highly modular and concurrent fashion (Koenig et al., 1997; Pal, 2015). Only upon delivery for construction is an integrated view of a ship's design realized; however, this integrated view

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Submitted: 23 February 2024, Revised: 1 May 2024, Accepted: 3 May 2024, Published: 19 May 2024

Conference paper, DOI: https://doi.org/10.59490/imdc.2024.842 e-ISSN: 3050-4864

is often only partially complete. In managing and operating the ship, multiple stakeholders may have incomplete interpretations of the ship as a whole due to its scale and numerous onboard systems.

Other ETO industries have also developed their own solutions to tackle these challenges. For example, in the aerospace and manufacturing industries, the use of 'digital mock-ups' (DMUs) (Oh et al., 2008) and generic AIMS (ISO, 2004b) as the equivalent of product data models is well-established.

Despite facing similar challenges related to high regulatory intervention, multi-organization, and customization (Emblemsvåg, 2014), the architecture, engineering, and construction (AEC) industry has seen significant digitalization in design and construction practices thanks to the introduction of the Building Information Model (BIM). BIM has helped solve these interoperability issues and continues to help advance the AEC industry's digitalization efforts (Azhar et al., 2008).

In light of the benefits of BIM, this paper aims to explore what the shipbuilding industry can learn from the AEC industry, focused on understanding potential improvements related to (1) data modeling and (2) collaborative design practices, including a temporal understanding of the system. In addition, this paper explores previous and current ship product data modeling attempts and proposes possible solutions that the shipbuilding industry can consider.

CURRENT PRACTICES IN SHIP DESIGN AND PLANNING

Today's ship lifecycle involves disparate processes, tools, and needs for each phase. These phases, covering upstream design to downstream operations and maintenance, differ in the generation, usage, and transformation of information related to a ship's product data model (Andritsos and Perez-Prat, 2000; Whitfield et al., 2003). Currently, product data models in shipbuilding are not similarly developed as an AIM according to ISO unless integrated platforms such as CADMATIC Wave and Siemens Teamcenter are used. When these tools are not used, a ship's design data is dispersed, involving a combination of a 3D model, drawings, and digital documents. Issues related to version control and change management are common, especially when multiple instances of these files are copied, modified, and not incorporated with other drawings. These practices perpetuate 'information silos' and decision-making with incomplete information (Stachowski and Kjielen, 2017). These gaps are most apparent in early design stages, where design uncertainty is high, but the most expensive decisions are made (Love and Sing, 2013; Mavris and Delaurentis, 2000).

While the lack of product information is the critical risk faced in early design, manual data integration is the concern in detail engineering. In detailed engineering, technical information is rapidly received from multiple cross-disciplinary sources, often in various file types and formats, as the focus shifts to technical evaluation and increasing design granularity. Where file formats are incompatible, manual exchange or conversion is expected. Dedicated integration engineers are often hired to ensure that all relevant drawings, documents, and models are consistent and incorporated into a technical package for delivery to a client or yard (NAVSEA, 2012; Gale, 2003).

Meanwhile, during construction, a shipyard's shopfloor planners are mainly concerned with developing transitional work packages that suit available resources, people, and time. Hence, the concern is not related to integration but to the translation and reorientation of design data into process data. Developing a bill of materials (BOM) and bill of processes (BOP), along with work packages, further leads to a ballooning of information that now incorporates planning and operations details (Pal, 2015). Post-commissioning, ship information must still be maintained in the downstream value chain to track the health of ship systems. All of this information remains in disparate onboard equipment and physical or digital copies managed by ship operators. Unfortunately, this type of data typically never goes back to ship designers to improve product information.

The differences in data management needs across a ship's lifecycle have led to the development of highly distinct and specialized software tools addressing particular ship design and planning functions, as shown in Figure 1 (Andritsos and Perez-Prat, 2000). However, this has also led to a paradoxical problem where, while there is now a greater range of ship design tools, the methods for exchanging data between these tools are outdated. It is not uncommon for these tools to have their own model and representation of a ship that remains isolated and spread organizationally or globally, with different levels of detail (LOD) (Erikstad and Fathi, 1999; Whitfield et al., 2003). The separation of ship data domains, continually being persisted by these disparate software, has led to a business culture where technical data development can be detached from the management and operations of such development process.

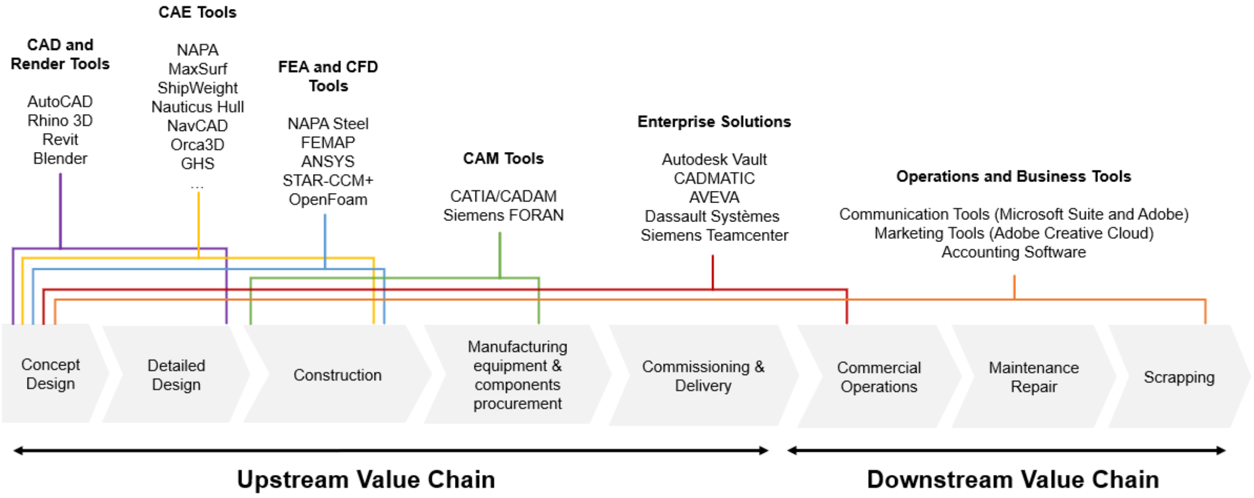


Figure 1: Disparate Tools with Overlapping Use Across the Shipbuilding Lifecycle

Integrating disparate ship data to produce a unified ship model is a highly complicated task. Before delving into the history of shipbuilding attempts, it is essential to note the following concepts on data exchange and management that shed light on the complexity of maintaining a product data model.

- ***Data Modeling*** – Data modeling focuses on how information is structured and how data relationships are represented (ISO, 2023, 2003). Typically, these relationships can be defined with human-readable diagrams, including IDEF, NIAM, etc.(Wyman et al., 1997), but they can also be represented in schemas such as relational database schemas and graphical database schemas (Härder, 2005) that are codified in implementation languages such as Basic, FORTRAN, C, C++, Java and EXPRESS. Several standards exist to help define what these schemas are, including the Knowledge Interchange Format (KIF), Web Ontology Language (OWL), and Resource Description Framework (RDF), which provide reasoning over how information can be represented in that domain (Rachuri et al., 2008). Concerns related to data modeling are typically focused on ensuring that product data models capture most of the information. Therefore, integrating information and managing increasing granularity or data fidelity are important considerations. This can cover product or even full enterprise integration, incorporating company and other resource planning data (Whitfield et al., 2003).
- ***Data Exchange*** – Data exchange is focused on the transfer of data across different applications and programs. To enable this, machine-interpretable syntax (defined in data formats) must be used to encode and share data digitally (Edelman et al., 2018) or direct translators are used when data formats are incompatible across software (Whitfield et al., 2003). The use of neutral file formats that can be interpreted by different software, as opposed to native file formats that are designed to be usable for only specific software, is therefore advisable. These neutral data formats for storage use extensions that vary based on the data contents, whether graphical (.IGES and .STL) or otherwise (.XML and .STP). When discussing data exchange, the concerns typically revolve around enabling interoperability. Hence, well-defined and formalized data models that can be used across industries ultimately help with interoperability. Hence, Open standards are typically related to data exchange, as are concepts pertaining to centralized or distributed data architectures. While there are plenty of neutral file formats, including XML and JSON, the ISO-certified format for interoperability is STEP, which uses the EXPRESS programming language (ISO, 2004a).
- ***Data Management*** – Data management relates to operations, systems, or tools that enable consistent and reliable data quality, security, and trustworthiness. Facilitating the use of data models and enabling data exchange is, therefore, just one of the few functions that efficient data management systems can help with (Samonas and Coss, 2014).

ISO 15926-1 defines data models relative to 3-layer database management (DBMS) architecture, emphasizing that data models should not be interpreted in isolation (ISO, 2003). The above elements can, therefore, be understood in terms of where they stack in this 3-layer architecture. Data models typically reside in the conceptual schema, data exchange is related to the dictionary and or interpreters for the conceptual schema, and data management is the infrastructure related to the database and applications or front-facing user interfaces.

DESIGN AND PLANNING REPRESENTATIONS USED IN SHIPBUILDING

Classification and Coding Systems

While there are now more widely accepted definitions of a product data model, it is essential to recognize the unique history of data modeling and shipbuilding. The challenge to arrive at a coherent product data model is not new; attempts have been made since the 1970s, starting with dimensional coding systems.

Ship classification and coding systems are still some of the most popular means of presenting ship data today. These systems were developed partly due to the popularity of modularity as a means to increase industrial competitiveness in the 1970s. These were heavily popularized by companies such as Boeing, who developed proprietary codes such as BUCCS-3 (Boeing Uniform Classification and Coding System) to streamline manufacturing processes. These classification and coding systems, also interchangeably called product structures, are hierarchical representations of an asset. These hierarchical product structures and modularity modernized shipbuilding, changing how shipyards were designed such that equipment and materials were laid out to enable the efficient execution of similar work types (NSRP, 1986). Coding systems are still widely used today (Oh et al., 2008) due to the relative simplicity and reliability of being used since the onset of modern shipbuilding practices.

Ship and Product Work Breakdown Structures. The Ship Work Breakdown Structure (SWBS) is one of the most widely used coding systems in North America. The SBWS, first developed by the United States (US) Navy in 1977, uses a 3-digit function-based code with main group divisions including hull structure, propulsion and electrical plants, outfitting and furnishings, integration engineering, and ship assembly and support. SWBS codes can be used to organize drawing schedules, material catalogs, work planning, work orders, craft labor, and cost collection. Unfortunately, while SWBS provided a means of organizing work, it could not capture the most effective information for accomplishing work, especially when complicated work packages are involved. Addressing these limitations led to the development of the Product Work Breakdown Structure (PWBS), which included work type, manufacturing level, zone type, problem area, and stage (Koenig et al., 1997; NSRP, 1986). The development of the PWBS classification system introduced additional domains as dimensions to SWBS representation based on cost, function, and tasks – leading to a three-dimensional understanding of a ship product as shown in Figure 2. However, the implementation of this dimensional coding system was time-consuming. Without automation capabilities, the PWBS codes were generated and retrieved manually via a massive PWBS Classification and Coding book that served as a dictionary for translating these three domains. Various attempts were made to digitize this process and manage coding systems using computers. One such example is the Decision and Classification Information System (DCLASS) from Brigham Young University. This generic tree processor proved to cut 95 percent of the time for data retrieval in cost estimation exercises.

Skipsteknisk Forskningsinstitutt (SFI) Coding System. In Europe, the widely-used alternative to the SWBS is the SFI Code, named after the Norwegian Skipsteknisk Forskningsinstitutt (SFI) that developed it. The SFI Code or System has a comprehensive product structure covering various aspects of ship and offshore specifications. SFI Code uses a 3-digit decimal code system to classify all ship and rig operation functions into ten main groups from 0 to 9 that cover the hull, equipment for cargo, and ship equipment, among others (Xantic, 2001). Officially launched in 1972 in Norway, the SFI Group was developed by a joint consortium of industry partners to establish a unilateral coding system that could be used unanimously among different shipyards and design stakeholders. The SFI Code was intentionally designed to be simple, applicable to all ships, and capable of future expansion. It was also intended to be a functional-oriented system for adaptability in design and production (Manchinu and McConnell, 1977).

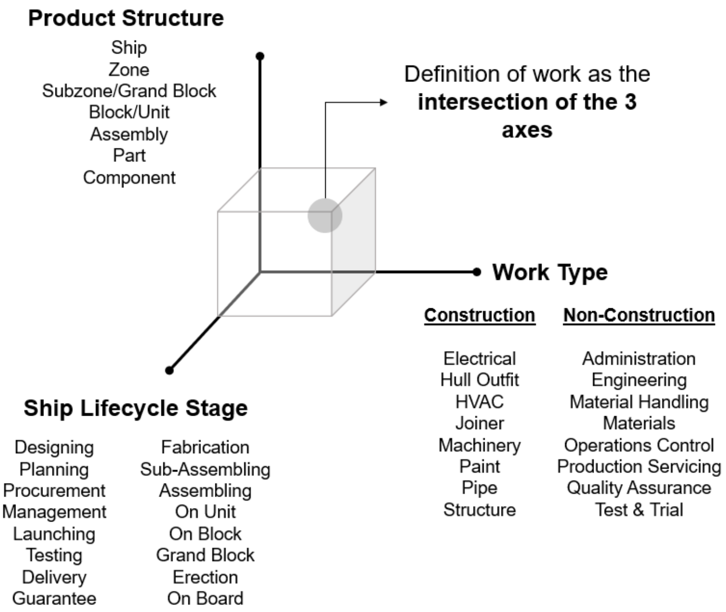


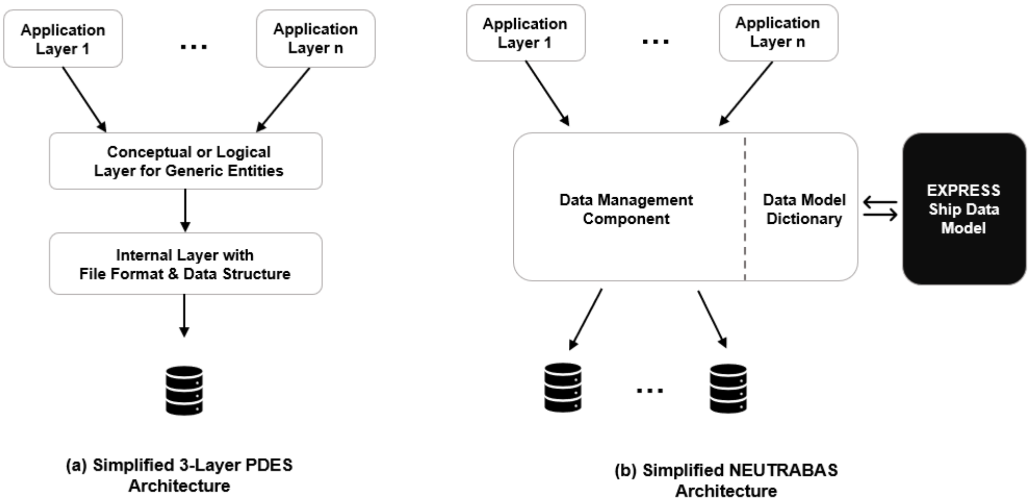
Figure 2: Dimensions in Generic Product Work Breakdown Structure (GPWS). Adopted from Koenig et al. (1997)

Ship Product Data Models

Product structures, especially with expanded domains and dimensions related to planning, faced hurdles in implementation due to the need and lack of tools to automate their usage. With the onset of computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) in the 1980s, ship designers and yards quickly picked up on the potential of these tools in improving technical design processes, which led to the natural integration of coding systems with modeling and 3D graphics. CAD/CAE/CAM enabled the transformation from coding systems to 3D graphical product-oriented information databases (Murphy, 1992). As such, what was involved in a digital product representation of a ship was relatively malleable from the 1970s to 1990s while both shipbuilding and software engineering were evolving rapidly (Ross, 1997; Gischner et al., 1997).

One of the earliest definitions of a ship product data model comes from Martin (1980), who described it as a ‘logically structured, product-oriented database’ that supports the analysis and informational needs for a ship’s engineering, design, construction, and maintenance (Whitfield et al., 2003; Ross, 1997, 2003). The use of the term ‘common model’ was ubiquitous, as multiple ship representations with varying embellishments across different departments were typical. Hence, a ship product data model was understood to support a certain degree of information integration, which can include enterprise data. Computer-integrated manufacturing (CIM) is an example of an enterprise integration concept, enabling testing, production, and control, all within a shared database.

These growing integration needs also led to interoperability issues that called for a serious assessment of digital information exchange standards (Gischner, 2006). International Standards Organization’s (ISO) STEP (STandard for the Exchange of Product Model Data), more formally known as ISO 10303, was launched in 1986 to solve cross-platform and cross-application development issues by producing a system-independent data representation (including geometry, topology, and functionality) of design artifacts (NSRP ASE, 2007). Its development was inspired by the Product Data Exchange Program (PDES), which tried to arrive at a consensus of a data exchange standard for industrial automation (Kelly, 1985). STEP largely followed traditional Database Management System (DBMS) Architecture at this time, which included a 3-schema architecture (as shown in Figure 3a) covering External Schema with user-facing applications, a Conceptual or Logical Schema for the translation of data via mapping or other logical representations of the system of interest, and the Physical Schema which involves the physical representation of the data as stored in a database (McDermid, 2013; Kelly, 1985). In this architecture, STEP was most concerned with the standardization of the components in the Conceptual Schema, which over time took the moniker of a data model as understood in software engineering today and as defined in ISO 15926 (ISO, 2003). The Conceptual Schema or Conceptual Model represents the view of the data negotiated between end-users and the databases, covering the meaning and the relationships of the data with each other. To facilitate this, the EXPRESS data modeling language was developed explicitly for STEP (Whitfield et al., 2003). This program prompted multiple initiatives for various industries to formalize their standards with ISO STEP in mind. In ship design and shipbuilding, the notable ones include NIDDESC and ISE from the US and NEUTRABAS from Europe.



(a) Simplified 3-Layer PDES Architecture

(b) Simplified NEUTRABAS Architecture

Figure 3: Simplified DBMS Architecture for PDES and NEUTRABAS. Adopted from Kelly (1985) and Nowacki (1995)

NIDDESC, 1986.The Navy/Industry Digital Data Exchange Standards Committee (NIDDESC) was developed in 1986 as a joint effort of the US Navy (NAVSEA) and the National Shipbuilding Research Program (NSRP), which focused on creating an industry consensus on the definition of product data and ensuring that these requirements were incorporated into national and international data exchange standards. The program's result was identifying product data model content for the marine industry and developing documentation for a neutral file format that incorporates IGES' specifications with the emerging STEP standards of that time. The developed documents were known as Application Protocols (APs) that defined the requirements for a ship's product information or Conceptual Schema for a specific domain. They converged to six APs submitted for inclusion into the STEP standards covering Piping, HVAC, Electrical Distribution and Wireways, Structural Systems, Outfit and Furnishing, and Standard Parts. These APs have been further refined into AP 215 for Ship Arrangements, AP 216 for Ship Moulded Forms, and AP 218 for Ship Structures, which are still usable today (Gischner et al., 1997; Murphy, 1992; Whitfield et al., 2003).

NEUTRABAS, 1989. NEUTRABAS is an EU ESPRIT-funded project to develop a neutral product understanding for ships and similar large multi-functional products. The NEUTRABAS project worked collaboratively with the NIDDESC program, which preceded it two years earlier. The project aimed to meet the following: (1) a formal definition of a ship product information model, (2) specifications for a neutral database technology, (3) implementation of a neutral database, and (4) the development of a prototype for pre and post-processors for neutral data exchange. (Welsch et al., 1991; Nowacki, 1995). The ship product data model they developed was written in EXPRESS and required a bespoke data management component (DMC) to facilitate communication between one system-specific format and any other system, as seen in Figure 3b. The NEUTRABAS effort was, therefore, one of the first to describe how a neutral model can be implemented outside purely providing recommendations on the Conceptual Schema. Regarding the model itself, NEUTRABAS and NIDDESC were similar and focused on the development of reference models but differed in the degree of integration between their reference models. While NIDDESC developed multiple models for different functional domains with discrete APs for piping, structures, etc., NEUTRABAS adopted the position that integrating all current and future shipbuilding APs required the standardization of a single comprehensive and high-level Ship Application Reference model. They deemed this a prerequisite to the interoperability of all APs (Nowacki, 1995; Welsch et al., 1991). This position helped to make a significant point about the importance of assessing the data structure to effectively manage the exchange of information across various complex and heterogeneous ship development applications.

ISE, 1999. The Integrated Shipbuilding Environment Consortium (ISEC) was established in 1999 with a group of shipyards and CAD vendors. It aimed to develop information interoperability solutions for US Naval shipbuilding in a series of NSRP initiatives called the Integrated Shipbuilding Environment (ISE) projects (Gischner, 2006). Specifically, the goal was to develop the next-generation Integrated Product Development Environment (IPDE). This open architecture information system supports the delivery of integrated acquisition, engineering, and logistics products for the naval ship lifecycle (Oh et al., 2008). It is understood to be the family of systems that maintains the digital product data model. With the growing popularity of enterprise software such as Product Data Management (PDM) and Product Lifecycle Management (PLM), these tools were naturally considered as implements to enable the IPDE capability.

Latest Initiatives (Early 2000s-Current)

The realization of a product data model with capabilities related to integration, interoperability, and data exchange remains a challenging task that is continually being addressed today. Central to this problem is the need for more clarity in defining how ship data should be presented and what domains of ship data should be incorporated (Gischner, 2006). These shifts are presented in Figure 4. Data modeling practices and paradigms have also grown and developed much faster than they could be formally implemented in this context. The evolution of data modeling paradigms is also presented in Figure 4 adopted from Patni et al. (2021).

STEP's EXPRESS language follows a hierarchical and entity-relationship-based paradigm, which requires rigid, well-defined relationships. For this reason, adapting and expanding the ship product data model with definitions based on AP 215 (for Ship Arrangement), 216 (for Ship Moulded Forms), and 218 (for Ship Structures) was a cumbersome process (Whitfield et al., 2003; Gischner, 2006; Kramer et al., 1992; Rando, 2001). Gischner (2006) states that it takes, on average, about 3 to 5 years to implement STEP. These STEP APs, in addition to needing plenty of information and time to implement, also required a constant effort to finalize and update to 'avoid stagnation and improve general uptake across the industry' (Whitfield et al., 2003). Ross and Garcia (1998) describe that multiple special-purpose tools are needed for STEP, one of the main inhibitors for broad acceptance into the industry. These challenges were recognized by ISO themselves, as reflected by the multiple changes done on the APs - from isolated guidelines to plug-and-play modules - to make them easier to adopt.

XML or eXtensible Markup Language was determined to be a credible alternative to the STEP EXPRESS language due to its broader support in the IT industry and more noticeable structure and hierarchy. However, while XML has more advanced data-sharing operations, such as enabling persistent storage of ship data from application to application, it is constrained by the amount of storage space it requires (Rando, 2001). This is a limitation with the massive amount of digital data involved in most ship design and shipbuilding programs today. A modern commercial vessel may be expected to have an associated product data model of 2 to 10 gigabytes in size, depending on its complexity (Whitfield et al., 2003).

Outside XML, extensive industry-led work has been done to define a standard exchange format, with the inception of the OCX (Open Class 3D Exchange) Consortium in 2021. OCX as a format was developed in 2016 by the APPROVED Industry project involving partners such as Aveva, Hexagon, Siemens, and NAPA aimed towards defining a format that can address the unique data exchange needs amongst classification societies and shipbuilders. Although some additional work is still required to support the use of OCX, the consortium is actively promoting its use with the aim of industry-wide adoption (Zerbst, 2023).

Along with these developments, interest has also risen in the concept of digital twins applied in maritime systems over the past decade. Digital twins are virtual prototypes of physical assets that have garnered attention for their ability to enable remote operations and co-simulation (Grieves, 2022; DNV AS, 2023). As of 2023, DNV published DNV-RP-A204, which provides best practices for implementing, assessing, and maintaining the functional elements (FE) toward realizing a digital twin. At the heart of the digital twin is a consolidated AIM, which incorporates multiple data domains per ISO 81346's class libraries. Along with the definition of the desired AIM, they also stipulate advanced change management processes (MOC+) to ensure the trustworthiness of the ship AIM throughout its usage. While they do not present specifics on the software side, this latest development recognizes the regulatory and class societies' perspectives on best practices to arrive at a cohesive model. Additional understanding and research on the challenges of digital twin implementation from a data modeling perspective, specifically in data fragmentation stemming from the transition from upstream to downstream lifecycle, are also studied deeper in Bronson et al. (2024).

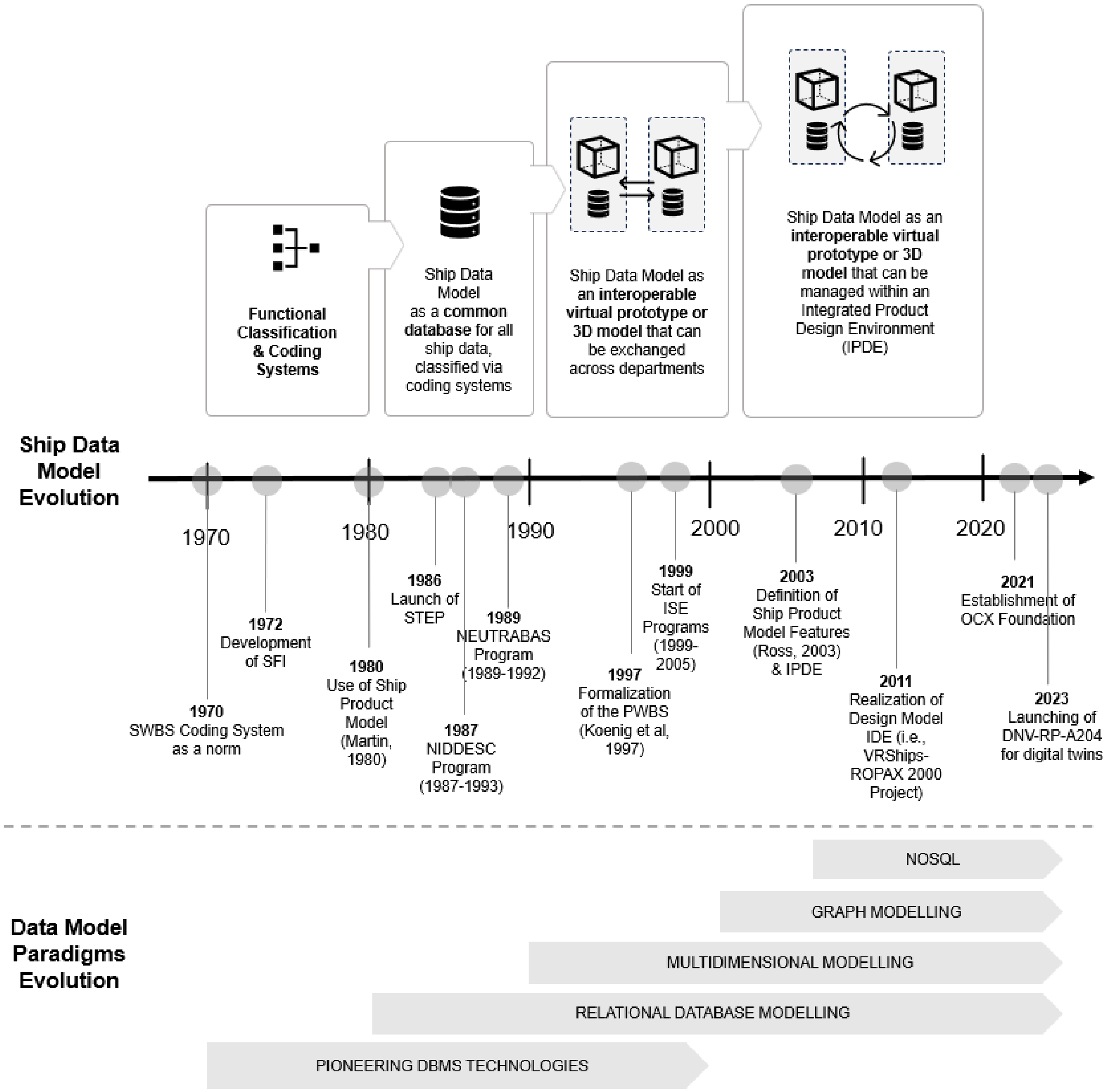


Figure 4: Evolution of Ship Data Concept

BUILDING INFORMATION MODELING (BIM)

Today, there is no tangible equivalent for the definition of a ship AIM except for that described by DNV for digital twins. In the AEC industry, the equivalent full building product data model is that of BIM. Like shipbuilding, the AEC industry had a notoriously long history of tackling data integration and interoperability issues, as shown in Figure 5.

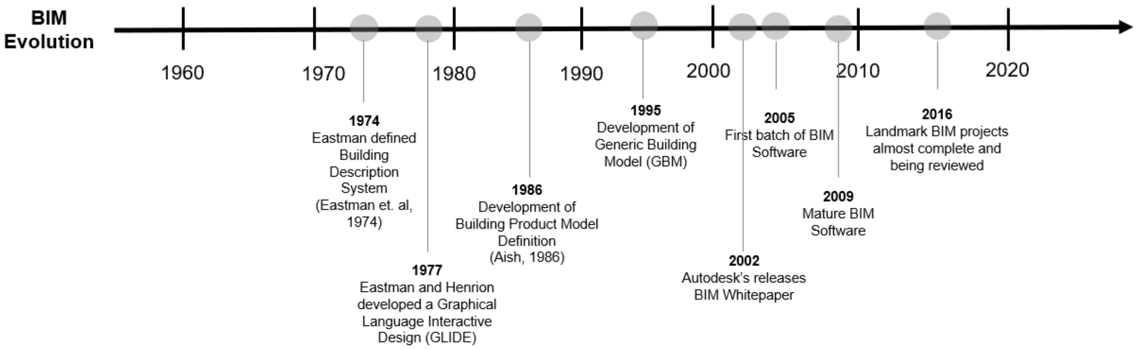
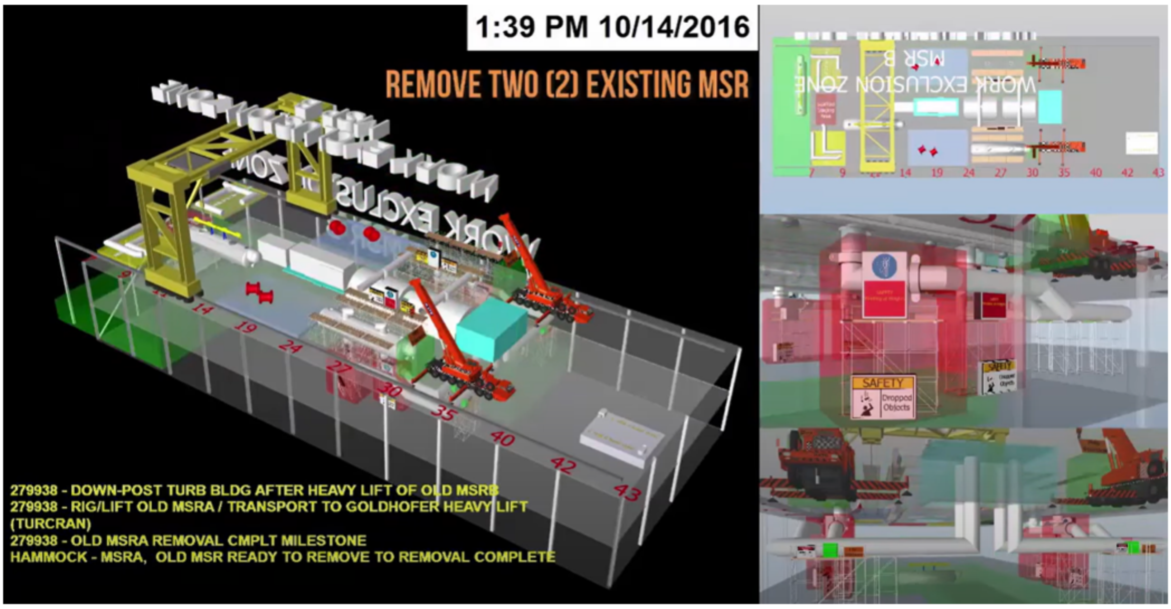


Figure 5: History of BIM, Adopted from Sinoh et al. (2020)

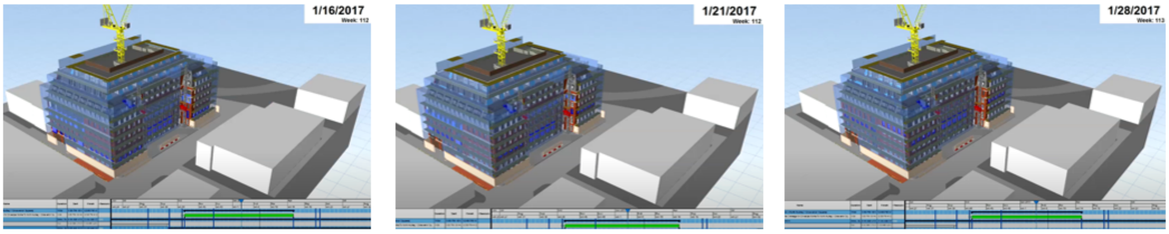
In a study by the US National Institute of Standards and Technology (NIST) in 2004, up to about USD 15.8 billion was lost annually due to 'the highly fragmented nature of the industry, the industry's continued paper-based business practices, a lack of standardization, and inconsistent technology adoption among stakeholders' (Gallaher et al., 2004). Although the knowledge of a cohesive building description system has been well-understood since the 1970s (Eastman et al., 1974), its formal implementation is a recent phenomenon. The original definition of BIM included three main elements: the structuring of design data, a digital model, and other non-graphical data, which were realized by bespoke tools such as RUCAPS in the 1970s (Aish, 1986). The implementation and broad commercialization of BIM as it is understood today were pioneered by commercial software companies such as GraphiSOFT, Bentley Systems, Autodesk, and Nemetschek AG (Autodesk, 2002; Wierzbicki et al., 2011). Autodesk's 2002 Whitepaper on BIM was one of the first to formalize a software strategy to implement digital databases, change management functions, and abilities to reuse information. In addition to formalizing a strategy, Autodesk also led the formation of IAI (Industry Alliance for Interoperability), now buildingSMART to understand the industry's take on data classes that can support integrated application development. This led to the development of IFC, in partial response to the slow adoption of STEP, as a neutral AEC product data model catered to the industry. Laakso and Kiviniemi (2012) describes this as one of the most ambitious standardization efforts in IT at that time. In addition to this formalization, the wide dissemination of BIM's practical uses has also influenced its success. As Azhar et al. (2008) cited, several case studies continue to encourage the use of BIM. Along with the iterative implementation and continued improvement of BIM came the modern understanding of it today as both a process and a tool.

According to the ISE (2021), BIM is a collaborative process enabled by technology, covering the whole lifecycle, from design and construction to asset operations. As a process, BIM allows the cohesive understanding of building data and fosters inter and intra-disciplinary collaboration. As a tool, BIM facilitates building data management across different lifecycle stages. Azhar et al. (2008) suggests the following benefits of BIM: (1) visualization, (2) fabrication and shop drawing support, (3) code reviews, (4) cost estimating, (5) construction sequencing, (6) conflict and collision detection, (7) forensic analysis, (8) facilities management, (9) quality take-off, (10) model-based estimating, (11) feasibility analysis, (12) alternative development, and (13) environmental analysis.

As there are different use cases for the application of BIM throughout a building's lifecycle, the qualitative and quantitative impacts of BIM overall are challenging to assess. However, in his study, Azhar et al. (2008) was able to share various scenarios where BIM has helped reduce costs in building projects. For example, the Atlanta Aquarium Hilton Garden Inn used BIM to plan the clash and collision detection. It identified about 55 clashes, resulting in a cost avoidance of over 124,500 USD. Similarly, BIM was used by the Emory Psychology Building for sustainability analysis, particularly in determining the most suitable building orientation, skin option, and position. In all these cases, BIM provided relative cost savings due to the ability to view and rapidly simulate different design possibilities.



(a) Synchro4D Combining Physical Model with Functional legend, task codes, and time simulations



(b) Time-frames from Synchro4D displaying time simulation and Gantt Chart

Figure 6: Synchro4D Project Simulations (SYNCHRO, 2017)

The overall trajectory of BIM development is focused on complete lifecycle management, as suggested by BIM dimensionality or ND modeling. This philosophy assigns informational dimensions of data to the building information model based on purpose. The current dimensions are accepted as 3D (for two spatial dimensions), 4D (for the inclusion of time), 5D (the inclusion of costs), and 6D (the inclusion of facilities management) (ISE, 2021). Although there is ambiguity surrounding BIM beyond the 4D version, it has piqued interest due to its potential to integrate scheduling data. The capabilities of 4D BIM, which enable simulated planning, is one of the most attractive features marketed by most BIM software today. For instance, Synchro4D, shown in Figure 6, displays the potential of viewing the physical model with task codes and time simulations from design to production (SYNCHRO, 2017). The advantages of 4D BIM have been realized in some projects to date, including the planning of Peachtree Mansion in Atlanta, Georgia. Determining how all resources should be coordinated and how the construction sequence can be optimized was highly beneficial (Azhar et al., 2008). This simulated design and planning is a functionality that other industries are not yet able to realize today, including the ship design and shipbuilding industry.

The following section goes through the critical features of BIM in terms of the product data model it uses and the collaborative processes surrounding the maintenance of such a model.

Features of BIM

Collaboration Mandated by BIM. BIM relies heavily on collaboration, which is well-established with BIM's definition of Levels of Maturity (LOM). BIM's LOM is defined as 'measures of how well each party's information is structured for use in the federation by a collaborator without requiring significant remodeling for their purpose' (ISE, 2021). There are currently three levels of BIM based on LOMs: Level 0 is unstructured, Level 1 is partially structured unfederated data, Level 2 is a structured federated information model, and Level 3 is a server-based object information model hosted on a queryable database. To meet Level 2 standards, which is the stage mandated in the UK for public projects (Cotter, 2023), data needs to be available for contractual client demands and stored in information-rich and federated 3D models. Other non-graphical formats should also be agreed upon, along with an execution plan to use and exchange data with such formats. Acceptable file formats include COBIe or Construction Operations Building Information Exchange (for exchanging meta-data) and other native data formats as long as they are specified in the BIM Execution Plans (BEPs) (ISE, 2021).

Structured and Federated Information Models. To cater to the specific needs of the construction industry, the IFC-neutral data schema was developed by IAI (currently buildingSMART) as a framework for the exchange of building information. IFC consists of multiple entities organized into an object-based inheritance hierarchy. The implementation of IFC into BIM solutions comes in the form of defining attributes for building components already present for the user in a BIM software. The benefit of using IFC is that the substantial number of these descriptive entities can enable a comprehensive view of building information. The IFC contains four conceptual layers in its building model: domain, interoperability, core, and resource. These layers follow a strict referencing hierarchy or ladder to ensure that the information is complete and easily maintainable (buildingSMART, b; ISE, 2021). Compared to STEP's AP 225, which is STEP's product model definition for building construction, IFC is also considered to have more representation possibilities (Chen, 2012; Burkett and Yang, 1995).

The latest version of IFC is the IFC4, which includes a definition of construction scheduling task via the ifcTask (buildingSMART, a). This entity enables the linking of building elements to the task of a construction schedule for simulation, as shown in Figure 7. Other entities in IFC4 include ifcresourcetime, which captures the time-related information about a construction resource, further linking time data with planning information. These definitions are the backbone of 4D BIM functionalities, as shown in Figure 6.

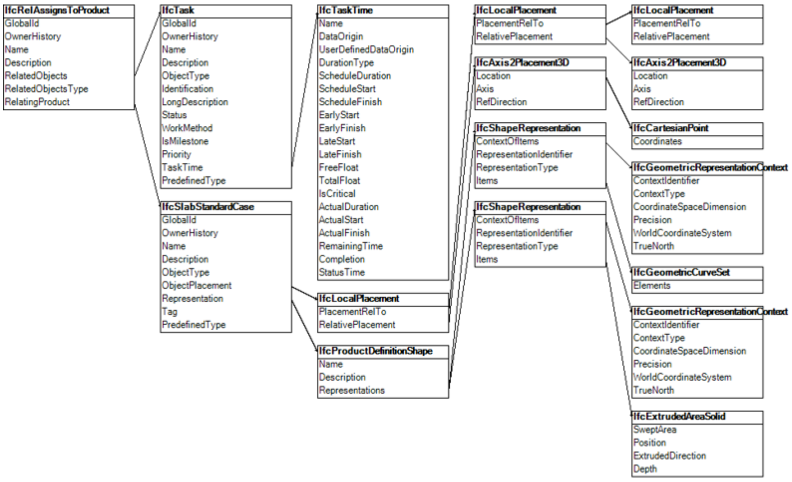


Figure 7: Definition of a IFC4 - ifctask Entity (buildingSMART, a)

Defined Process for Implementation and Maintenance. It is crucial for companies implementing BIM to have a well-defined pipeline that encourages collaboration and ensures compliance with BIM mandates. Without the use of BIM workflow, the benefits of BIM would not be realized. Several documents are necessary for implementation – including the Exchange Information Requirements (EIR) and BEPs. Hence, in trying to execute BIM, companies must ensure that (1) a clear articulation of what information is required from each participant is contained in the EIR document and (2) a definition of how each participant will provide such information is written in the BEPs. Defining goals, project milestones, and procedures for data exchange is therefore crucial in the BIM process (ISE, 2021).

To help facilitate these processes, a shared data environment called Common Data Environment (CDE), as shown in Figure 8, is used. In BIM, a CDE is a centralized system that compiles, manages, and distributes all project documentation. CDE also defines the states for developing and sharing a version of the design before it is handed over to the client. Without proper enforcement of these procedures, the risk still exists of creating isolated islands of information and outdated versions of the building model in the process (ISE, 2021; Borrmann et al., 2018).

Due to the availability of platforms that enable a seamless adoption of BIM today, BIM has become a standard practice in countries like Finland, Singapore, South Korea, and the US. BIM is mandatory for government projects in some countries, such as the UK (Cotter, 2023). Client demands and regulations have led to a vast proliferation and development of tools that deliver BIM capabilities, which today include Autodesk Revit, Autodesk Navisworks, GraphiSOFT ArchiCAD, Bentley Arch, and TEKLA, among others (Rice, 2010).

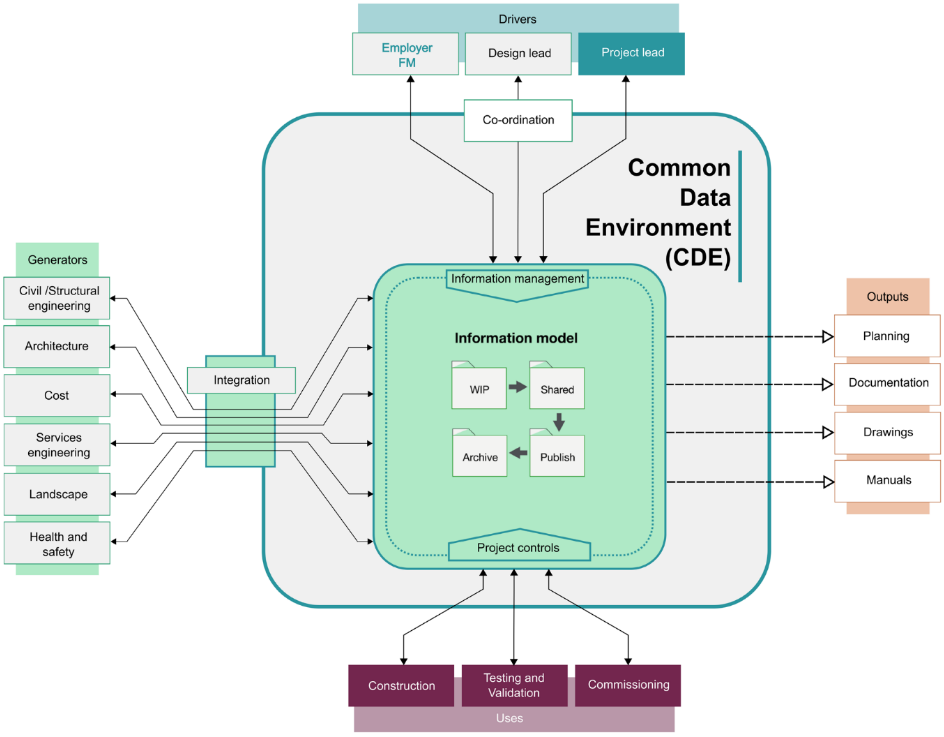


Figure 8: BIM Common Design Environment (ISE, 2021)

DISCUSSION AND COMPARISON

This paper has so far highlighted the ongoing efforts of both shipbuilding and AEC industries to improve asset information management. While the AEC industry has made significant progress with the use of BIM, the shipbuilding industry still needs to catch up in developing and adopting a standardized ship product data model. While both industries are unique, there is potential for cross-industry learning, especially from the shipbuilding side.

In both AEC and shipbuilding, the definition of the product data model is more or less analogous to each other. The differences mainly lie in the development and maintenance of such product data models. While current efforts, as with DNV-RP-A204's adoption guidelines (DNV AS, 2023), provide policies and aspirational procedures for addressing these gaps, the actual implementation has not been fully realized. We converge to four gaps in the adoption of a cohesive ship product data model, including an assessment of where BIM's solutions stack in addressing these gaps:

1. Undefined ship product data model representation that is unable to incorporate multi-domain ship data incorporating time, process, and functional information
2. The lack of industry-wide data exchange standards impeding interoperability
3. The lack of an IPDE that impedes collaboration
4. The lack of data management protocols to support the IPDE, modeling standards, and exchange standards

Inflexible Ship Model Representation and undefined exchange standards. Current data modeling standards are outdated to suit the shipbuilding industry's needs. The rigid representations defined in ISO standards, unfortunately, impose the following challenges: (1) they are not easy to customize for the wide range of shipyards today, and (2) they are not flexible for the diversity of projects (proposals vs. detailed) in a single company that has varying LODs. The latter also applies to the variety of customers ship designers may need to cater to, whether commercial or government clients. Customizing a product data model, as it is structured today based on ISO standards, to suit these diverse needs is infeasible, and the reuse of a ship product data model as a template is not practical unless ship systems are entirely transferable (Oh et al., 2008). The amount of disclosure that is possible based on client preferences or security protocols also impedes the transfer or reuse of design templates. Pollini and Meland, in a 1997 paper where they developed a bespoke Smart Product Model (SPM) for a shipyard, expressed that creating a product modeling system bespoke to a yard took an enormous amount of effort, where 'over 30,000 methods and object-oriented databases on the order of 2.5 gigabytes of data' were generated (Whitfield et al., 2003).

Well-defined product data models that are widely accepted help enable interoperability. Consistency in expressing data increases the successful exchange of information. Currently, the standardization required for information exchange remains vague, and ISO ship APs are limited to their respective domains, so there is limited focus on a comprehensive and holistic view of ship design information.

BIM manages the balance between collaboration and information security by utilizing tools and standards to create detailed and robust building information. In addition, it requires parties to define the extent of collaboration and agree upon neutral or native formats to use in the project through the use of BEPs and EIRs. BIM does not enforce a single solution but is flexible enough in implementation to suit the needs of the parties involved, whether these parties themselves have strict data security protocols or otherwise. This flexibility is reflected in the degrees of LOMs that clients can choose from. A similar framework can be applied to the shipping industry, whereby the level of federation in the data model and the degree of interoperability can vary to suit the diversity in the project types and client preferences. This can also cover various diverse LODs within a ship design company so that a lower level of federation can be applied for designs or early concepts with minimal design granularity. For more mature designs involving multiple parties, a high level of federation could be applied.

While this flexibility exists, BIM is still able to provide reliable and robust means to generate a comprehensive view of the building data via the IFC model. To compensate for the challenges of manually defining the model, IFC is intended to be used complementary with BIM software where .ifc files can be generated easily. This software can be used at various stages of maturity of a design, such that it is compatible with designs with low and high data fidelity.

Lack of Data Management Protocols and Integrated Development Environment (IPDE). Provided formats exist to enable data exchange, an environment that allows and facilitates this exchange can only be fostered with collaboration. Enabling this environment is not yet well understood in commercial and large-scale contexts in shipbuilding, as open standards are not the norm and shipbuilding stakeholders are heavily dispersed. Luming and Singh (2015) cites that the shipbuilding's position in collaboration can best be described with the One-CAD Solution, which is a mentality focused on using the same CAD tools to reduce interoperability and communication issues. This mentality, however, locks shipyards to specific proprietary software.

BIM addresses these issues by primarily focusing on collaboration. The success of BIM implementation relies heavily on two factors - the availability of BIM tools and the shared ownership of the BIM process among the technical team and management. These BIM tools are intended to provide a secure and common design environment or CDE, covering the database and data management components. The shared ownership of the BIM process incentivizes the disciplined use of these tools to make the most of their capabilities.

NOTES FOR DEVELOPERS

Shipbuilding has a long history of attempts to handle dense technical and planning databases. This has presented an ironic dilemma where the industry has a good understanding of the challenges that come with big data but needs to have updated data management solutions. This paper converges to reevaluating what is possible with technology-driven and culture-driven changes related to product data management. Specifically, highlighting the following considerations for future developers:

1. Implementation of industry-acceptable data modeling and data exchange standards custom to shipbuilding needs
2. Development of an IPDE environment for managing custom ship product data models

A BIM-like solution that incorporates multi-domain product data models specific to the industry and managed within a collaborative IPDE environment can help realize 4D Shipbuilding akin to 4D BIM. Despite the challenges that already exist in the definition of a ship product data model, as listed in the previous section, investing in the potential of a BIM-like solution is still worthwhile, provided the aspirational capabilities this model can provide, as summarized in Figure 9.

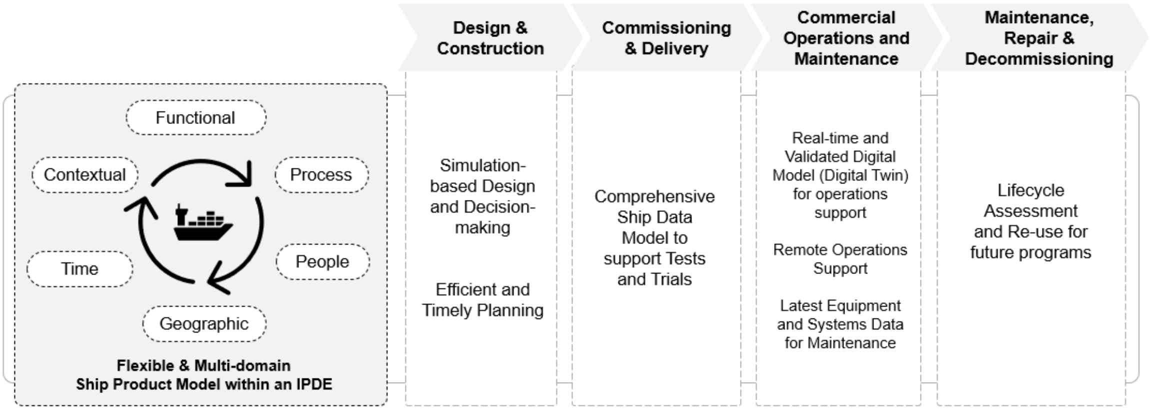


Figure 9: A Multi-domain and Federated Ship product data model to support various lifecycle phases

Today, no single tool has transformed the ship design and shipbuilding industry like BIM. An ongoing project that aims to fill this gap is the EU HORIZON SEUS Project, addressing inefficiencies in ship design and operations using computational tools (Gaspar et al., 2023). Gleaming into software practices, the project aims to tackle the challenges of defining, using, and managing a ship product data model throughout its entire lifecycle to reduce the time of ship production by 20 to 30 percent.

A current paradigm the project is investigating is graph data modeling. By investigating a more flexible data modeling paradigm, as opposed to the existing rigid entity-relationship models commonly used today, it may be possible to establish connections across multiple data domains with minimal effort. In addition to investigating ways to develop a multi-domain ship product data model, the project aims to understand interoperability solutions and create a PLM software to encourage collaboration among various stakeholders. Other considerations it aims to note include data quality and security of the model, noting risks that may be posed by lack of data accuracy and cyber security. These developments are done with close industry and academic collaboration, hoping to explore solutions that can realize the same impacts BIM has had in the AEC industry.

CONCLUSION

This paper reviewed the history of initiatives related to adopting and understanding a cohesive ship product data model. It was found that despite shipbuilding's long history of tackling interoperability issues, actual solutions to address these problems remain limited. The inflexibility of ship product data models, the lack of technology enabling an integrated design environment (IPDE), and the absence of data exchange standards in the industry were consistently determined to be limiting factors in the realization of ship product data models.

BIM, especially the concept of 4D BIM from the AEC industry, poses a refreshing take on solutions to address these issues in their sector. It demonstrates the importance of standards related to product data modeling. BIM's CDE, a digital centralized platform for developing and sharing building design and operations data, can be a template for shipbuilding's IPDE concept. Additionally, IFC, as BIM's modeling schema that currently encapsulates not only geometrical data but also time data, proves the possibility of a multi-domain product data model that can be used to integrate planning and design domains. Future developers can take inspiration from these elements to create a platform, bespoke for shipbuilding, that addresses interoperability in today's software practices. The success of BIM, not only as a tool but also as a process, may also encourage ship design and shipbuilding managers to incorporate technology-enabled collaboration for more efficient ship design and operations.

CONTRIBUTION STATEMENT

Author 1: Writing – original draft; conceptualization; data curation; visualization
Author 2: Conceptualization; supervision
Author 3: Conceptualization; supervision; project administration
Author 3: Writing – original draft; conceptualization; data curation

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