



# SEUS

## Smart European Shipbuilding



# D1.1 - RESULTS AND ANALYSIS OF THE BEST PRACTICES RESEARCH



This project has received funding from the Horizon Europe Framework Programme (HORIZON) EU programme under grant agreement No 101096224.

**Project no.** 101096224  
**Project acronym:** SEUS  
**Project title:** Smart European Shipbuilding  
**Call:** HORIZON-CL5-2022-D5-01-06  
**Start date of project:** 01.01.2023  
**Duration:** 48 months  
**Deliverable title:** Results and Analysis of the Best Practices Research  
**Deliverable No.:** D1.1  
**Document Version:** V0.3  
**Due date of deliverable:** 30 June 2024  
**Actual date of submission:**  
**Deliverable Lead Partner:** Partner No. 1, NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU  
**Work Package:** 1  
**No of Pages:** 55 (Report) + 86 (Appendix)  
**Keywords:** European shipbuilding, ship design, shipbuilding, best practice

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#### Dissemination level

|    |        |
|----|--------|
| PU | Public |
|----|--------|

#### History

| Version | Date       | Reason              | Revised by                                      |
|---------|------------|---------------------|---|
| 01      | 31.05.2024 | First version (JH)  | Jisang Ha and Janica A. Bronson (NTNU)          |
| 02      | 19.06.2024 | Second version (JH) | Jisang Ha and Magnhild K. Wolff (NTNU)          |
| 03      | 26.06.2024 | Final version (HG)  | Henrique M. Gaspar and Magnhild K. Wolff (NTNU) |

# Executive Summary

This document is a review of the Best Practices in Shipbuilding in Europe and developed as part of the EU Horizon Program on the Smart Shipbuilding Project (SEUS). This document is connected to the SEUS Best Practices Baseline (Milestone 2, M12), Deliverable D1.1 – Results and analysis of the best practices research (M18), and Deliverable D1.2 – Result and analysis of the survey (M18). This version is updated in size and scope from the version presented at the SEUS Workshop on November 15th (Netherlands).

The objective of this work is to provide an overview of the State of the Art of Shipbuilding in Europe, focusing on the aspects tackled by the SEUS Project, as stated in D1.1: *“Results and analysis of best practices research (...) will be presented as descriptive summaries, user stories, and other research material (articles, synopsis for white papers, abstracts of research, etc.) in a what that can be used further for software development input and as a coordination canvas of the project.”*

There are plenty of resources and literature that provide a detailed overview of the characteristics of European shipyards and shipbuilders relative to foreign competitors. These studies provide insights into opportunities to increase efficiency within these yards and challenges to get there from a theoretical or high-level perspective. However, limited research is available that delves into the practices that exist within these yards, owing to the competitive nature of the industry and since shipyards can vary in business and shipbuilding strategies. Our report aims to shorten the information gap on the understanding of what short-, medium-, and long-term planning looks like in European yards, improve the information fidelity to map how ship information generation evolves into a built physical realization throughout the lifecycle of the vessel. The report includes references from the state of the art, as well as material developed during the first 18 months of the SEUS project.

By consolidating practices currently applied in European shipbuilding, this report aims to demonstrate what a shipbuilding lifecycle looks like from conceptualization to delivery, focusing on potential improvements and gaps in our understanding of what these phases entail. To potentially streamline the vessel lifecycle within the framework of SEUS' goals and ambitions, this report also intends to draw focus on information management throughout the lifecycle of the vessel, introducing taxonomies that are used in practice and how they evolve or relate with one another throughout these lifecycle phases.

The report was supplemented by 'Comprehensive Best Practices Research in European Ship Design and Shipbuilding', which contains an extended version of references, figures, graphs and material that can be presented in a slide deck format. The research is attached as Appendix A, and is complimentary to this report.



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# 1. Best Practices Research and Analysis in Shipbuilding at the SEUS Project

## 1.1. EU Shipbuilding and SEUS Project

Digitalization and computational tools have great potential to generate value for improving the competitiveness of the EU shipbuilding industry. It requires a significant reshaping of existing tools and practices to be exploited successfully. The gains come in the form of increased quality and reduced time required for design, virtual prototyping, estimations of impacts for the use of greening innovative technologies, modularization, flexible data management, interoperability across proprietary tools, cyber security, efficient support for modern robotized fabrication and openness for integration with operational platforms. The future of shipbuilding lies in the smarter use of computational tools.

The main goal of the Smart European Shipbuilding Project (SEUS) is to create a Smart Shipbuilding Framework for European shipyards. This is achieved by architecting and developing an integrated platform for a combined and integrated solution incorporating CAE, CAD, CAM, and PDM software and testing it at shipyards. The new platform solution will be built with the best European shipbuilding expertise provided by academic and industrial consortium participants. It intends to develop novel practices for human-centric knowledge management in shipbuilding, the use of NLP, and data-driven AI design elements in the current consensus or intelligent technologies and Industry 5.0.

With effective integration of these features, the project aims to ultimately increase the efficiency of shipbuilding across the entire lifecycle of the vessel, as presented in Figure 1.

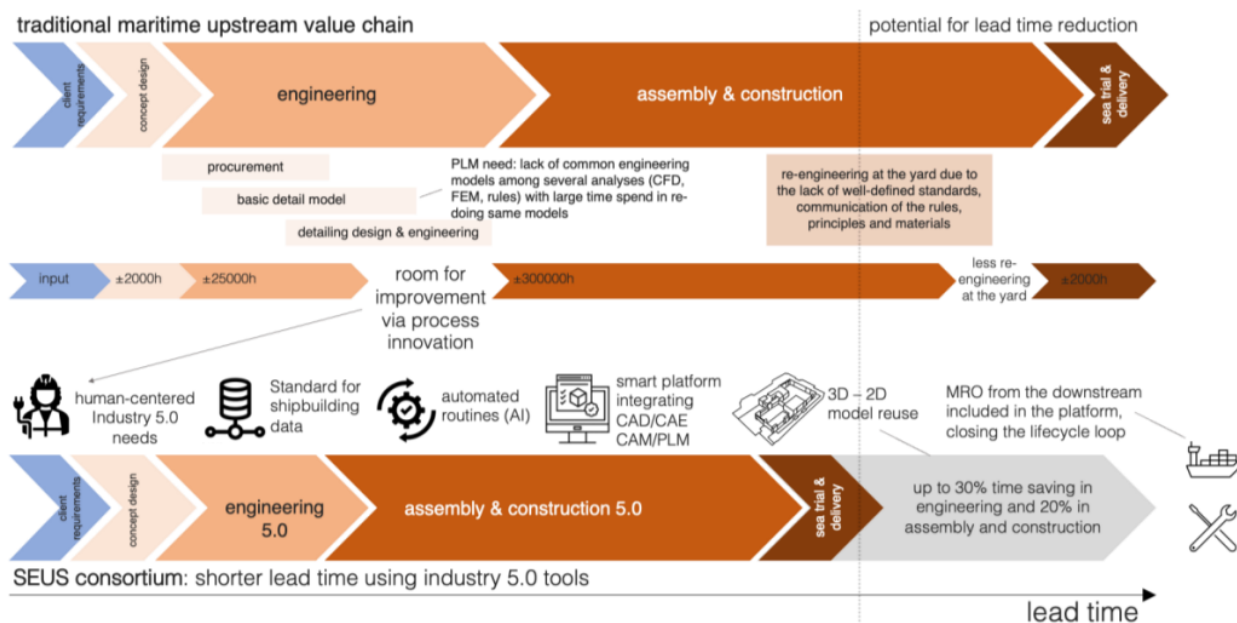


Figure 1 - Potential for Lead Time Reduction [98]



## 1.2. Reasoning and Approach to Best Practices

This report addresses research, evaluation, and compilation activities to identify the best practices for the smart PLM approach in shipbuilding (WP 1). It aims to build a new body of knowledge for the value shipbuilding can expect to gain from digitalization, a single-source of truth approach with compelling information and data sharing for all stakeholders. The relation of this work package to the goal of the overall SEUS project is described in Figure 2.

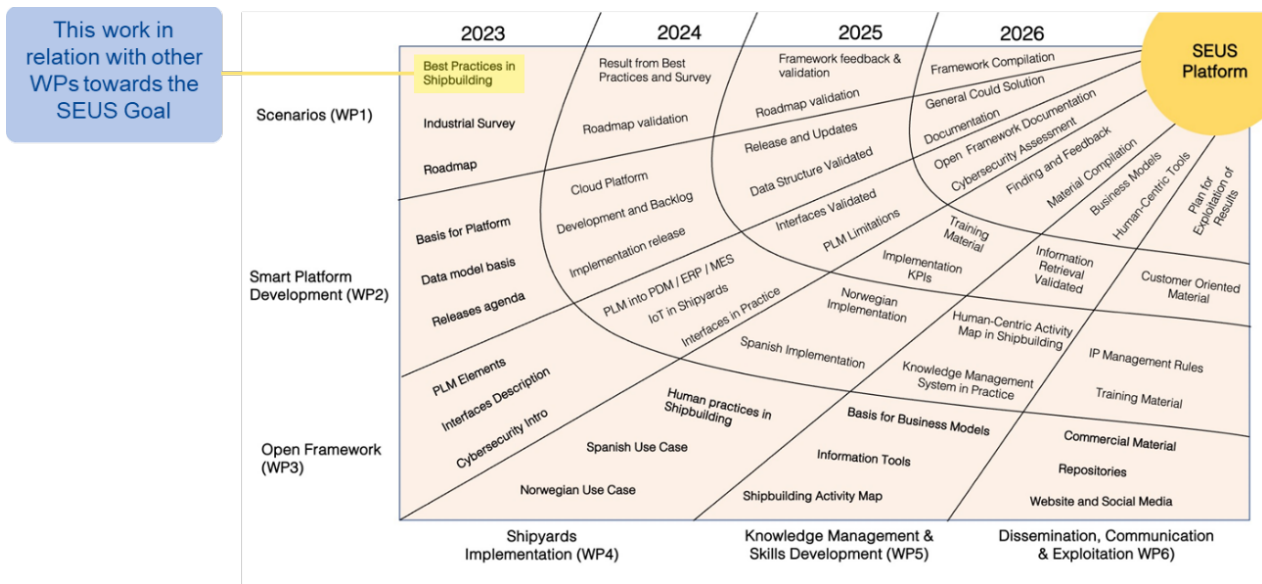


Figure 2 - The Relation of Work Package 1 to the SEUS Goal (Internal data of SEUS from NTNU)

The European shipbuilding industry is unique due to its focus on custom and specialized ships, heavy multi-organization, and offshoring strategies. European maritime cluster and ecosystem are well-positioned to tackle digital transformation. Better ship data management can enable more effective (1) decision-making and planning, (2) communication between disparate stakeholders, (3) knowledge retention, and (4) risk management.

An effective digital solution can tackle integration challenges that exist across domains (functional, physical, people, time, process, and context), parties involved, and ship lifecycle phases. Solutions focused on lifecycle management, such as PLM, can help to promote a cohesive view of the ship model data. However, enterprise solutions such as PLM or ERP still face challenges in terms of adoption, time for training, and lack of interoperability with existing third-party tools.

With this BP research report, we aimed to develop a diagnosis of the current state of the European shipbuilding industry and investigate the conditions and background for creating the necessary digital solutions.

The results and analysis of the best practices research are presented in two parts. The first part is in Section 2. Best Practices in European Ship Design and Shipbuilding. Secondly, the report is supplemented by the Comprehensive Best Practices Research in European Ship Design and Shipbuilding, which contains an extended version of the analysis, with references, figures, graphs, and material that is presented in a slide deck format. The research is attached as Appendix A.

## 2. Best Practices in European Ship Design and Shipbuilding

### 2.1. Overview of the Topics

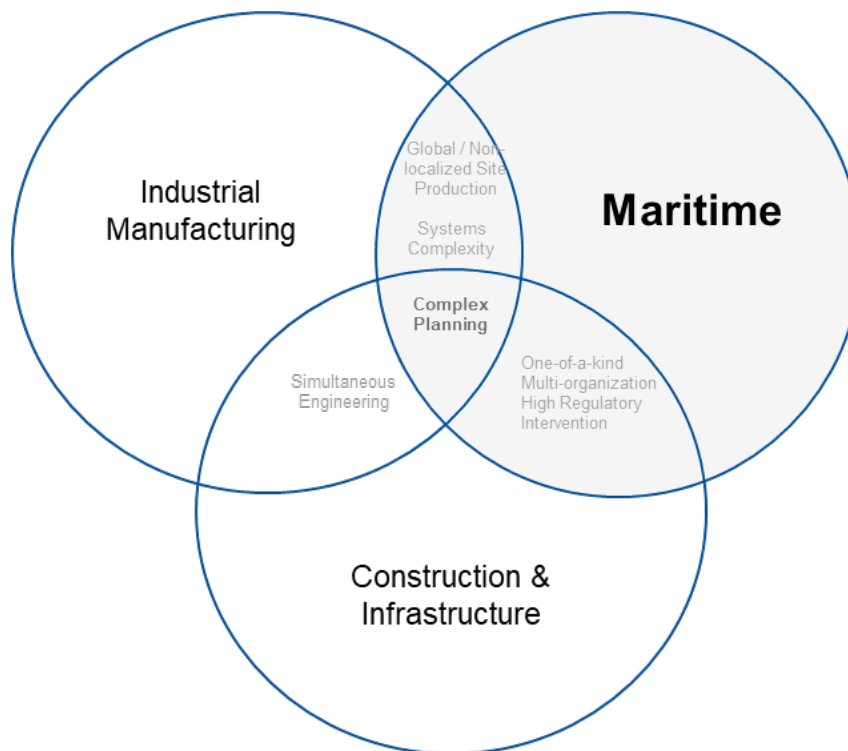
This report highlights the complexities and best practices in European ship design and shipbuilding, with the integration of Computer-Aided Design (CAD) and Product Lifecycle Management (PLM) systems. The report outlines the ship design and shipbuilding process, breaking it down into various phases from concept design to construction. It identifies key challenges facing the industry, such as the need for improved collaboration, risk management, and decision-making throughout the lifecycle of a ship. By using digital tools and frameworks, the industry can address these challenges more effectively.

The document also discusses various PLM functionalities and details how these tools can streamline processes across different domains (contextual, geographic, people, functional, product) and tasks/process-based. It emphasizes the need for better data integration and management through the concept of a Single Source of Truth (SSoT), which aims to consolidate all relevant information into a cohesive, accessible platform. With respect to the intent, this report explores the current state of digitalization in ship design and shipbuilding, covering the following themes:

- EU Place in Shipbuilding Market – Current trends in European ship design and shipbuilding industry.
- The Ship Design and Shipbuilding Process – Current practices and logical stages in the ship upstream lifecycle.
- The Ship Design and Shipbuilding Toolbox – The state of digital tools used in the industry and paradigms in how ship data is represented in ship design and shipbuilding.
- Distinctions in Ship Design and Shipbuilding – Unique perceptions and challenges to the application of lifecycle management tools in ship design and shipbuilding.
- Single Source of Truth (SSoT) Concept or Attempt – Attempts to develop an SSoT solution.

### 2.2. EU Place in Shipbuilding Market

The Maritime Industry is a peculiar and one-of-a-kind industry. The industry takes on unique features from both manufacturing and construction. As it falls between craft production (Engineer-to-Order) and continuous production (Assembly-to-order), best practices from either industry are not directly transferrable as shown in Figure 3. Emblemvåg [1] outlined, four peculiarities of the maritime industry. Temporary multi-organization, 2. Site Production, 3. One-of-a-kind nature of products, 4. Regulatory Invention.



*Figure 3 – Features of the Maritime Industry*

Ships are more complex to manufacture than other craft vessels, both in terms of size and manufacturing difficulty. A 537-ton Airbus A380 comprises four million individual parts from 1,500 companies from multiple countries globally [2]. On the other hand, an USS NIMITZ Aircraft Carrier has about a billion parts [3].

Four main markets comprise the Maritime Industry and drive the supply/demand of vessels globally. The freight market, the sale and purchase market, the building market, and the demolition market are four main markets as shown in Figure 4. Of these markets, the ship design and shipbuilding (SD&SB) market is the most capital-intensive to disrupt. Complications arise due to 1. High product complexity, 2. Lack of product and process information, 3. Low-Risk appetite due to regulatory and safety risks, and 4. Need for external incentives to drive change.

SD&SB market is heavily influenced by these global maritime trends, along with local production factors and a wide-range of clientele needs. SD&SB clientele may vary from the navies, cruise lines, large shipping and freight companies (COSCO, Maersk, Frontline, etc.), shipping industrial conglomerates (Hyundai, Mitsui, Kawasaki, etc.), oil companies, offshore contractors, and other entrepreneurial shipowners. There are 5 main types of products in SD&SB Industry: Trading vessels (oil tankers, bulk carriers, containerships are the 3 highest-volume ship types), Offshore vessels, Industrial vessels, Passenger vessels, and Naval Vessels. SD&SB Industry covers a wide range of services and companies providing these services of ships. Companies support the design, build, operations, and decommissioning of a ship throughout the entire vessel's lifecycle. Figure 5 shows an example of ship lifecycle.

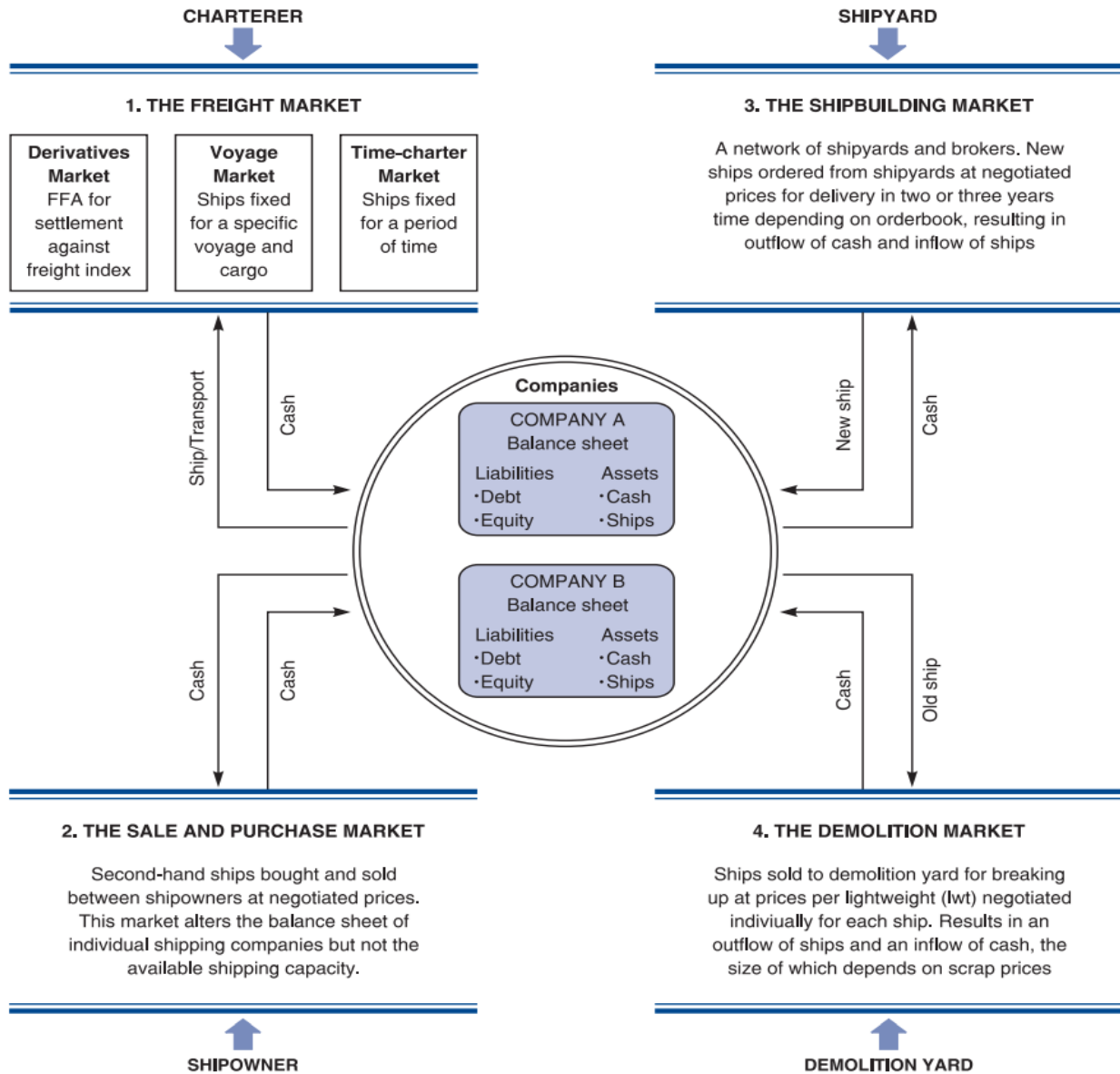


Figure 4 – Four Main Markets Comprise the Maritime Industry [4]

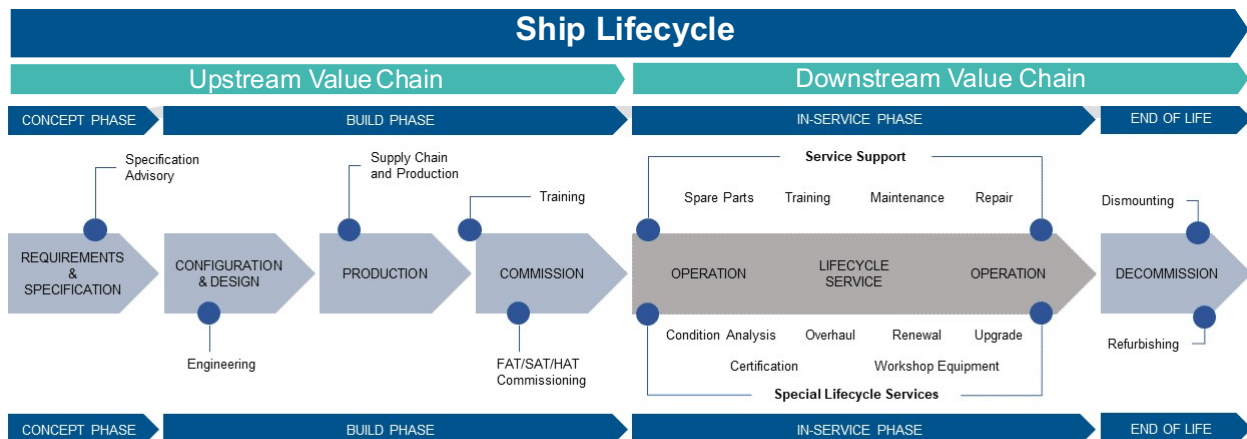


Figure 5 – An Example of Ship Lifecycle and Value Chains [5]

Stakeholders of the SD&SB Industry are highly coupled throughout the lifecycle of the vessel. Companies ranging from design firms, yards, operators, suppliers, and scrapping yards all closely work together from the ship design and manufacturing stages to scrapping and recycling as shown in Figure 6.

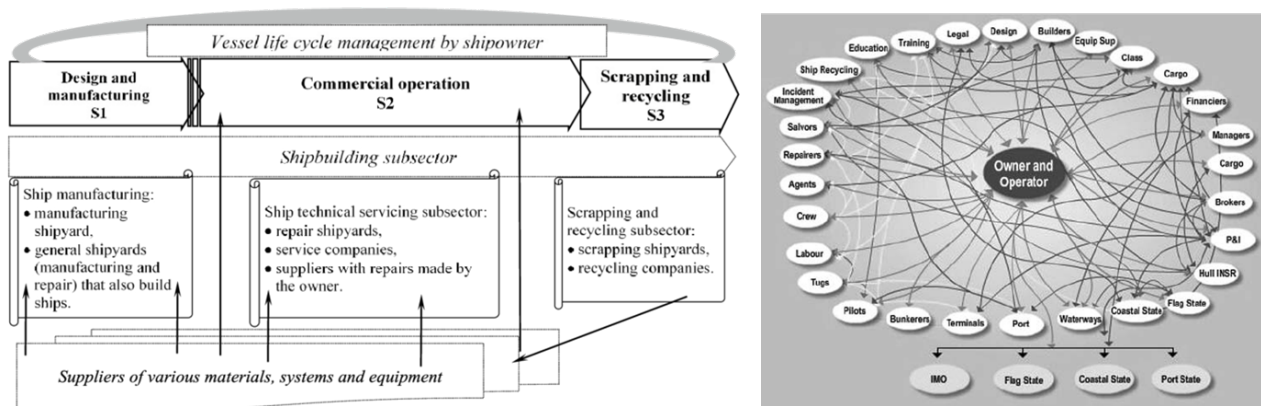


Figure 6 – Stakeholders of SD&SB Industry [6], (Adopted from [7])

In this complex SD&SB Industry, Europe’s current position is unique as a specialized niche player, where (shipbuilding and ship design) segments are characterized by a high degree of specialization and high-technology qualities, complex production processes, in combination with limited numbers of vessels of the same type that are to be built [8]. As echoed by the studies from SEA Europe 2023 [9] this specialization is driven by market reasons. European shipyards have lost a considerable part of their market share to East-Asian shipyards which are now leading suppliers of cargo ships, tankers, and containerships [9]. Despite a highly distributed network of stakeholders worldwide, Asian shipyards have become economically attractive due to lower labor and materials costs. Up to 81% of global newbuild deliveries come from China and South Korea while Europe only shares about 7%. Figure 7 shows the overview of shipbuilding activity in 2023 by country or region (in mCGT).

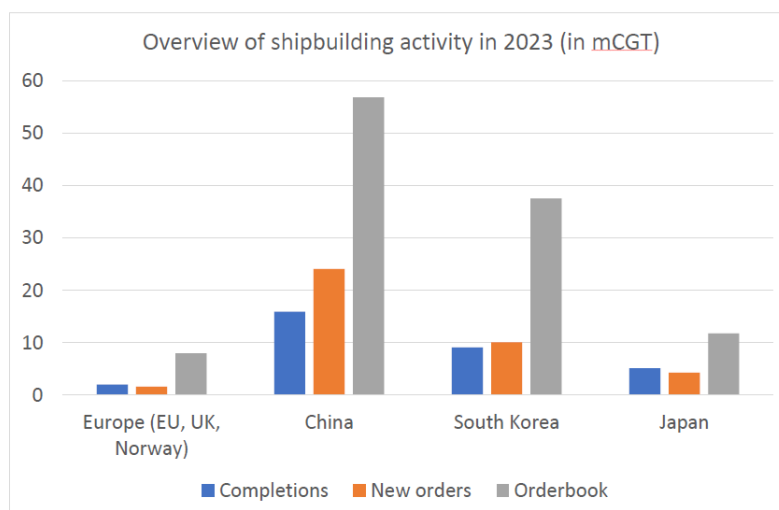


Figure 7 – Overview of Shipbuilding Activity in 2023 by Country or Region [9]

Common ship types like container vessels, gas, dry bulk, and tankers have the highest demand among vessel types. These ships are mainly produced in non-European yards. To remain competitive, Norway and most European shipyards are focused on assembling complex ships, with about 60-80% of the value of the ship procured as systems and modules from a wide network of suppliers' [10] as shown in Figure 8.

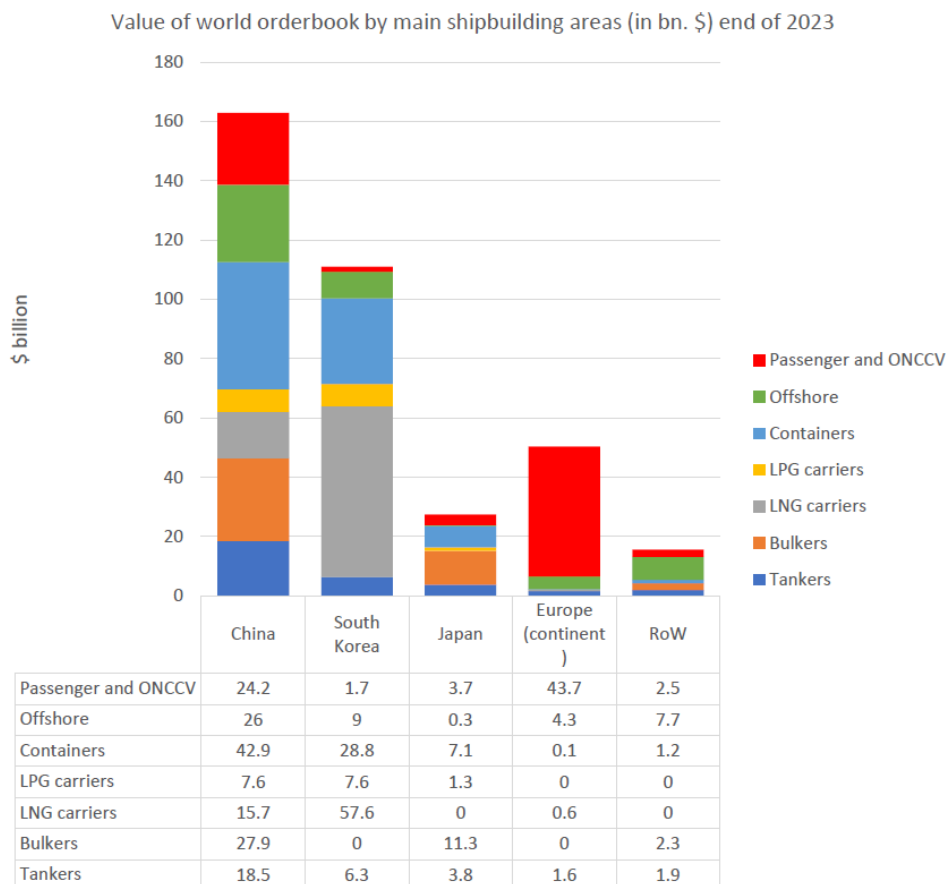


Figure 8 – Global Trends in Commercial Ship Deliveries [9]

These characteristics of European shipyards create a fragmented ship life cycle spread across multiple stakeholders, from ship design firms to shipyards, and marine equipment manufacturers. Due to a higher degree of vessel specialization and customization expected in the European market, streamlining the manufacturing workflow is not as easy to accomplish. Europe dominates the passenger and non-carrying cargo (NCC) vessels market to distinguish itself from competitors. In 2022, Europe comprised around 78% of global passenger vessel deliveries and around 30% of specialized vessels.

Although the number of newly constructed ships produced by European yards is relatively low, they still constitute a significant percentage of global new orders market value. Based on Clarkson Research, Europe was responsible for 55% of the total value in global new orders in 2016, primarily due to its focus on building expensive, specialized, and customized ships [11]. Highly specialized vessels and complex NCC ships include passenger ship, fishing vessels, dredgers, platform supply vessel, seismic vessel, wind farm installation vessels, they are considered big segments in the future. Over the years, Europe continues to grow in the passenger and NCC vessel markets, with passenger vessels comprising around 88% of the EU orderbook as of 2022.

Due to continuous investments in complex vessels and Research and Development (R&D), European Original Equipment Manufacturers (OEMs) are the largest marine equipment suppliers worldwide. European companies supply about 52% of the maritime equipment worldwide. From 2010-2014, the average production value was around 71.3 billion euros. European shipyards have adapted to new demands by offshoring the construction of certain ship parts to keep costs low, allowing them to focus on complex outfitting and repairs. For instance, in the North Sea, yards focus on ship repair and new builds. About 8% are scrapping shipyards [12]. There are about 150 yards in Europe and roughly 40-50 (first-tier yards) are active in the global market for large seagoing commercial vessels, comprising 7% of global yard capacity. These first-tier yards manage to utilize up to 80% of their capacity in 2022. Capacity dropped in 2023 due to long building periods but a 105% utilization demand is expected in 2024. This high yard utilization demands high-efficiency yard planning as shown in Figure 9.

**Share of global orderbook (%) and yard capacity (million cgt)**

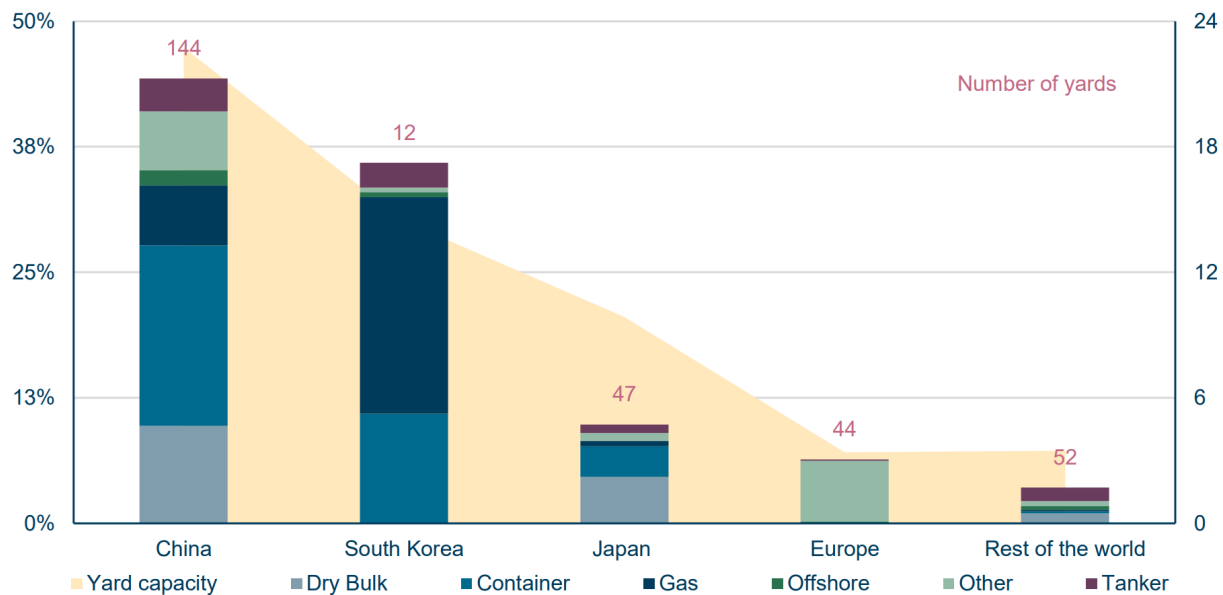


Figure 9 – Shipbuilding Market Share of Global Orderbook and Yard Capacity [13]

Global Shifts and Sustainability Goals also increase the overall uncertainty and volatility in the market. UNCTAD’s uncertainty factors related to the maritime industry are driving changes not only in regulatory maritime policy but also in influencing ship demands and maritime solutions (Adopted from [14] as shown in Table 1.

Table 1 - UNCTAD's uncertainty factors related to the maritime industry [14]

| Geopolitics and Trade Dynamics   | Environment  | Industry 4.0 Trends  |
|--|--|--|
| <p>US-China Trade Tensions affecting tariffs</p> <p>Race for Arctic Resources</p> <p>Tension in Maritime Chokepoints Structural shifts in globalization patterns</p> | <p>Accelerating environmental and regulatory agenda</p> <p>Melting of Polar Caps</p> <p>Rising Sea Level</p> <p>Ocean Acidification</p> <p>Ocean Pollution (and the subsequent effects on food supply)</p> <p>GHG Emission</p> | <p>Automation and Robotics</p> <p>Internet of Things (IoT)</p> <p>Big Data, ML/AI</p> <p>Advanced Materials</p> <p>Biotechnology</p> <p>Renewable Energy</p> |

Due to increased focus on environmental regulations, a large portion of today's fleet may be part of the future's demolition pool. Clarksons' research has estimated that about 30 to 40% of today's yard capacity is needed to decarbonize the fleet. Also, the improvements in operational efficiency and logistics can enable ships to be more sustainable. Up to 20% of fuel savings can be attained with better vessel utilization and alternative route planning [15].

Maritime rules and regulations are not only governed by global regulatory bodies (such as IMO) but also by classification societies. Classification societies, selected based on flag state requirements, are organizations that develop and apply technical standards for ship design, construction, survey, and inspection. These shifting maritime laws and regulations mean design thresholds related to safety and the environment change year after year. Designers must stay up-to-date with policies as work templates and reference designs may not always be transferrable. For example, the case of regulatory considerations in Canada, environmental pollution regulations that may affect ship layout, tankage arrangement, etc.: CEPA, Oceans Act, Canada Shipping Act, Ballast Water and Sediments, MARPOL 73/78, SARA, Wildlife Act.

In summary, European SD&SB market is faced with a few unique features. The industry is designed to maximize custom and specialized ships (from OEMs to ship-type investments) which requires a high degree of systems integration in both design and construction. Extreme multi-organization with yards abroad requires high collaboration and robust data security. Limitations in shipyard capacity and yard utilization require specialized facility planning. A unique maritime ecosystem means that the European market is well-placed to tackle sustainability challenges and explore innovative market segments but needs low-risk strategies to do this.

In this situation, how can European SD&SB remain innovative but also increase production efficiency? As the production efficiency curve suggests, trade-offs between product innovation and process efficiency exist. One of the optimal set of conditions that can enable high product innovation and process efficiency for the European market is digitalization. Awareness of the benefits of digitalization

has increased to handle the rising design and construction complexity and business uncertainty in the SD&SB market. The motivation behind digitalization ranges from increasing business competitiveness to asset reliability, which includes the need for advanced manufacturing and operational solutions. Studies and assessments show that there are multiple opportunities for process improvement with digitalization across the ship's lifecycle, from ship design to operations. Also, there are business opportunities with a projected market of up to 5.5 billion USD by 2030 on maritime digitalization, especially in digital shipyards as shown in Figure 10. European interest in digitalization can be attributed to the large number of OEMs already present in the region, which are themselves facilitating advanced digital solutions for their equipment.

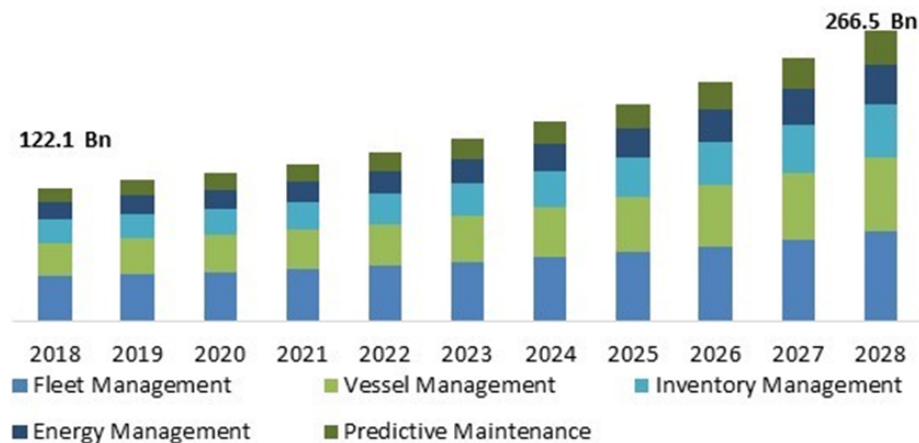


Figure 10 – Expected Maritime Digitalization Market Size by Application [16]

In summary, European SD&SB market has unique features. The industry is designed to maximize custom and specialized ships (from OEMs to ship-type investments) which requires a high degree of systems integration in both design and construction. Extreme multi-organization with yards abroad requires high collaboration and robust data security. Limitations in shipyard capacity and yard utilization require specialized facility planning. A unique maritime ecosystem means that the European market is well-placed to tackle sustainability challenges and explore innovative market segments but needs low-risk strategies to do this. And there are opportunities in digitalization. Maritime digitalization can help to drive business competitiveness and meet global sustainability goals. The European maritime cluster and ecosystem are perceived to be well-positioned to tackle digital transformation.

## 2.3. The Ship Design and Shipbuilding Process

### 2.3.1 Ship Concept Design

The focus of the SEUS project is on the upstream value chain. In this section, the Ship Design (concept and detailed engineering) and Shipbuilding (Construction) phases are explored as shown in Figure 5. Compared to the downstream value chain, the upstream activities are cost-intensive due to the level of engineering and labor required. Upstream stages are broken down into: Concept Design (covering preliminary ship design), Detailed Engineering (covering contract and functional engineering), Intermediate Engineering (or production engineering), Steel Construction, Parts Fabrication, Outfitting (covering on-block and onboard outfitting), Launching, Delivery, and Testing, Commissioning. In Ship Design Phase, Concept Design and Detailed Engineering are introduced.

To manage these external pressures, European shipbuilding and building strategies are quite distinct. [17] reviewed about the different building strategy elements that deviate from the conventional upstream value chain. Despite the formalization of these build strategies, as detailed by [18] and [19], the degree to which this strategy is formalized and used as a strategic approach varies among shipyards.

The upstream value chain begins with Concept Design (or Conceptualization or Pre-contract phase). Concept Design is focused on elucidating the client’s requirements into a package to win a bid and/or to get class approval. By breaking down the client’s requirements into high-level specifications, the ship designers can prioritize certain ship functions and mission systems for analysis, feasibility studies, or high-level concept design. A functional breakdown of the ship (i.e., Structure, machinery, propulsions systems, etc.) is used to systematically identify priorities. This phase is client-focused and can be highly collaborative with the client depending on whether there is a high degree of customization required.

For custom designs, ship design begins with requirement elucidation and ensuring that the vessel can perform the expected operations or ship mission. There are several approaches to ship design, from the traditional design spiral to more modern approaches such as model-based and set-based design as shown in Figure 11.

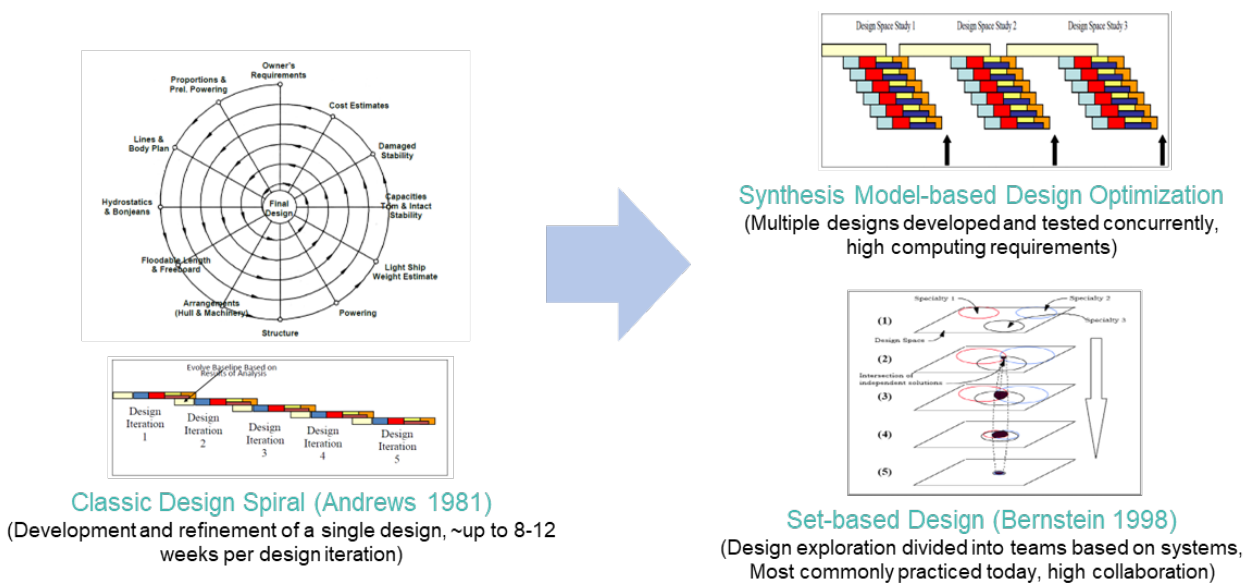


Figure 11 - From the Traditional Design Spiral to More Modern Approaches [20]

At each ship design cycle/iteration or model, naval architects and designers assess critical ship features and perform design activities. From hydrostatics, hydrodynamics, and other perspectives, a number of activities are performed, including Ship Weight Estimation and Area/Volume Assessment, Intact Stability Assessment, Damage Stability Assessment, Propulsion Trade-off Analysis, Vessel Performance Evaluation, Electric Load Assessments, General Arrangement (GA) Drawings, Safety Compliance Review. However, common ship design activities are not always performed linearly.

In the early stages of design, automated methods with low-fidelity data can be used for the systematic exploration of the design space. However, decision-making itself at this phase can't be automated due to close client collaboration and the lack of design information. Flexibility and collaboration are

key in early concept design. To manage multiple engineering variables and cost estimates related to ship design, naval architects and marine engineers need to understand various design trade-offs (via design matrix or similar). For instance, ship speed as a design variable influences several design activities, including vessel range and endurance, propulsion system requirements, fuel capacity, the volume and area of machinery spaces (affecting the General Arrangement and layout), the volume and area of tankage (impacting stability and weight), and overall costs. When deciding on ship speed, several trade-offs must be considered. These include lower costs versus improved vessel performance and mission capabilities, simplified hull form versus increased ship stability, simplified structure versus enhanced General Arrangement (GA) flexibility, and increased structural complexity versus reduced weight. Understanding these trade-offs is crucial for making informed decisions that balance performance, cost, and operational requirements.

Due to the interactions between design activities, ship design especially the concept design is highly complex due to dependencies between parts (or combinatorial complexity) and due to uncertainty. Figure 12 shows the relationship between uncertainty and complexity.

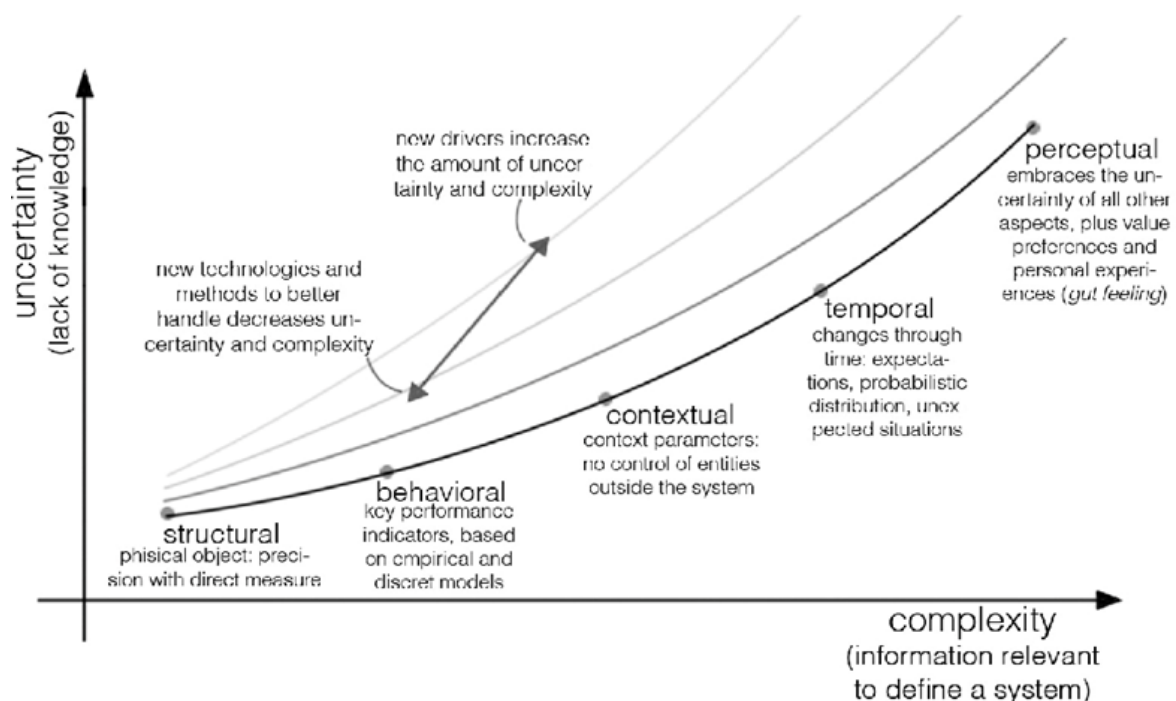


Figure 12 - The Relationship Between Uncertainty and Complexity [21]

To drive effective decision-making, reference (historical or analogous) data and contextual knowledge are critical in the concept design. Errors in this phase are cheaper to amend. Risk margins and adjustment factors are commonly used at early design to manage the lack of certainty. Rule-of-thumb thinking and experience become highly relevant, as opposed to theoretical design thinking which can be time-consuming and costly to implement. In the context of variable estimation in the concept design, various methods can be approached, such as analogous estimation, parametric estimation, and engineering estimation. For instance, to estimate the weight of a ship comprising approximately 700 components (excluding steel parts), analogous estimation utilizes historical data from a comparable system or subsystem, with appropriate adjustment factors applied. Similarly, parametric estimation involves statistical analysis of past projects, utilizing weight ratios or derived equations. Conversely, engineering estimation entails a bottom-up detailed assessment, which, is often time-

consuming. The method relies on actual costs, typically derived from documented expenses of previously constructed ships of the same design, is hindered when such data is unavailable. In instances where weight estimates prove completely erroneous, triggering potential repercussions for design integrity and future costs, the iterative process of design may necessitate a restart, underscoring the importance of vigilant monitoring and adjustment throughout the project lifecycle. Figure 13 shows variable estimations in the concept design stage at Ulstein [22].

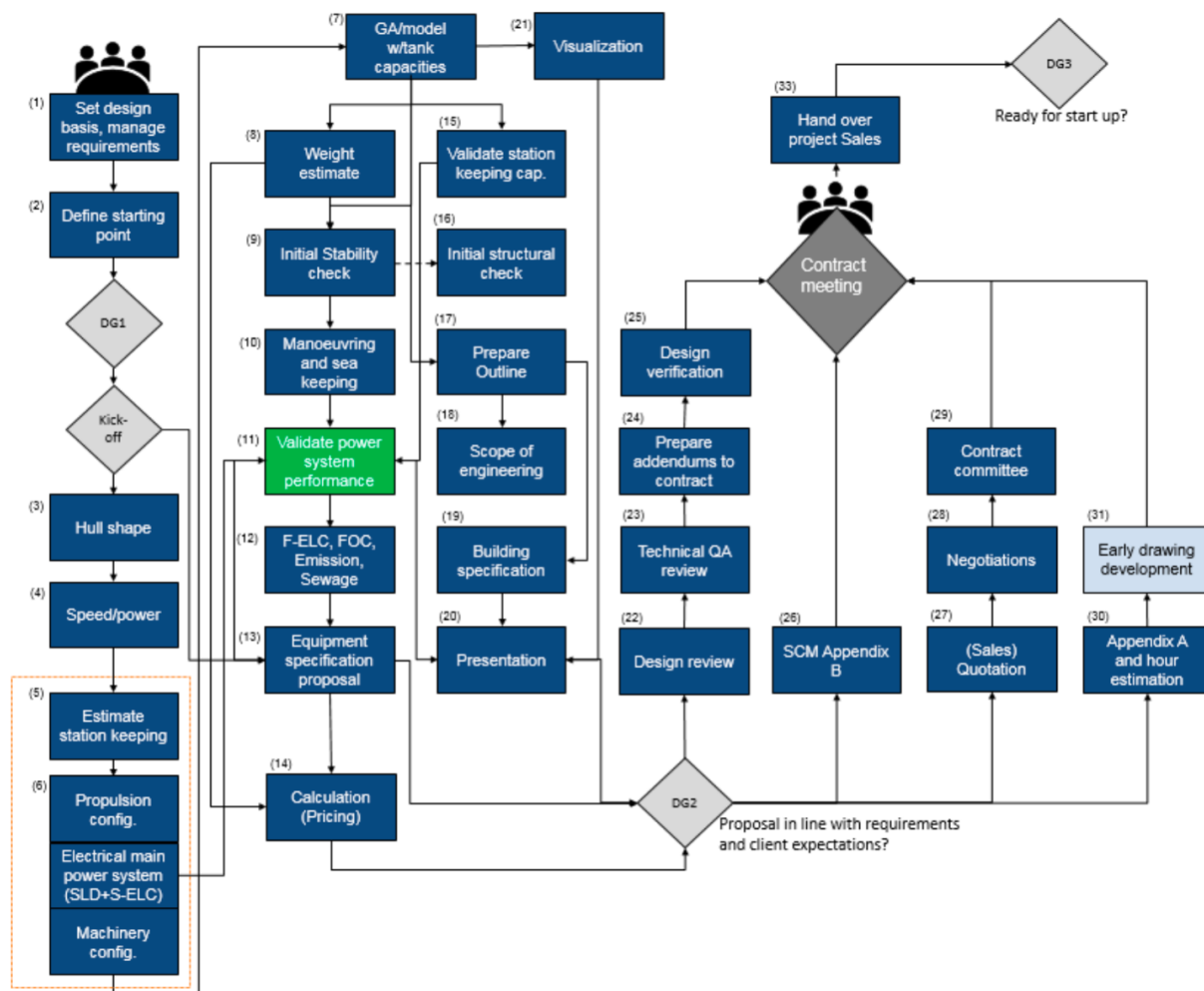


Figure 13 - Concept design with variable estimations: Sample Process Execution [22]

### 2.3.2 Ship Detailed Design

When the high-level concept is defined, further granularity in design definition and evaluation is performed in the detailed engineering. Unlike concept design, there is less uncertainty in the design and there is a shift in focus to ensuring feasibility is assessed and details are complete. To handle the complexity of a vessel, the ship is often broken down by function or systems. Figure 14 shows an example of the ship which is broken down by function and systems.

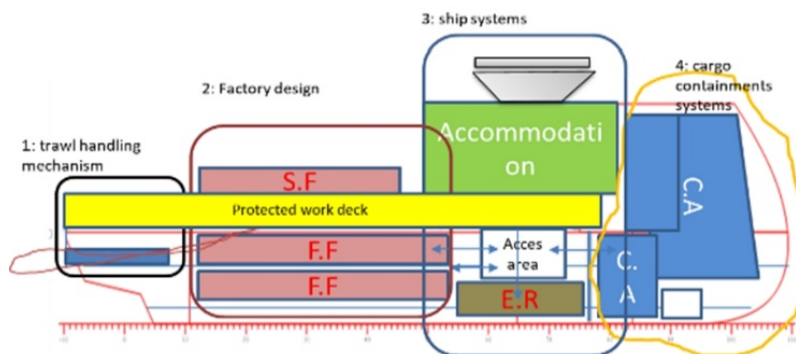


Figure 14 – An Example of the Ship Broken Down by Function and Systems [23]

Ship breakdown standards such as Ship Work Breakdown Structure (SWBS) and SFI are commonly utilized and have been in use since the 1980s. Figure 15 shows an example of SWBS Breakdown.

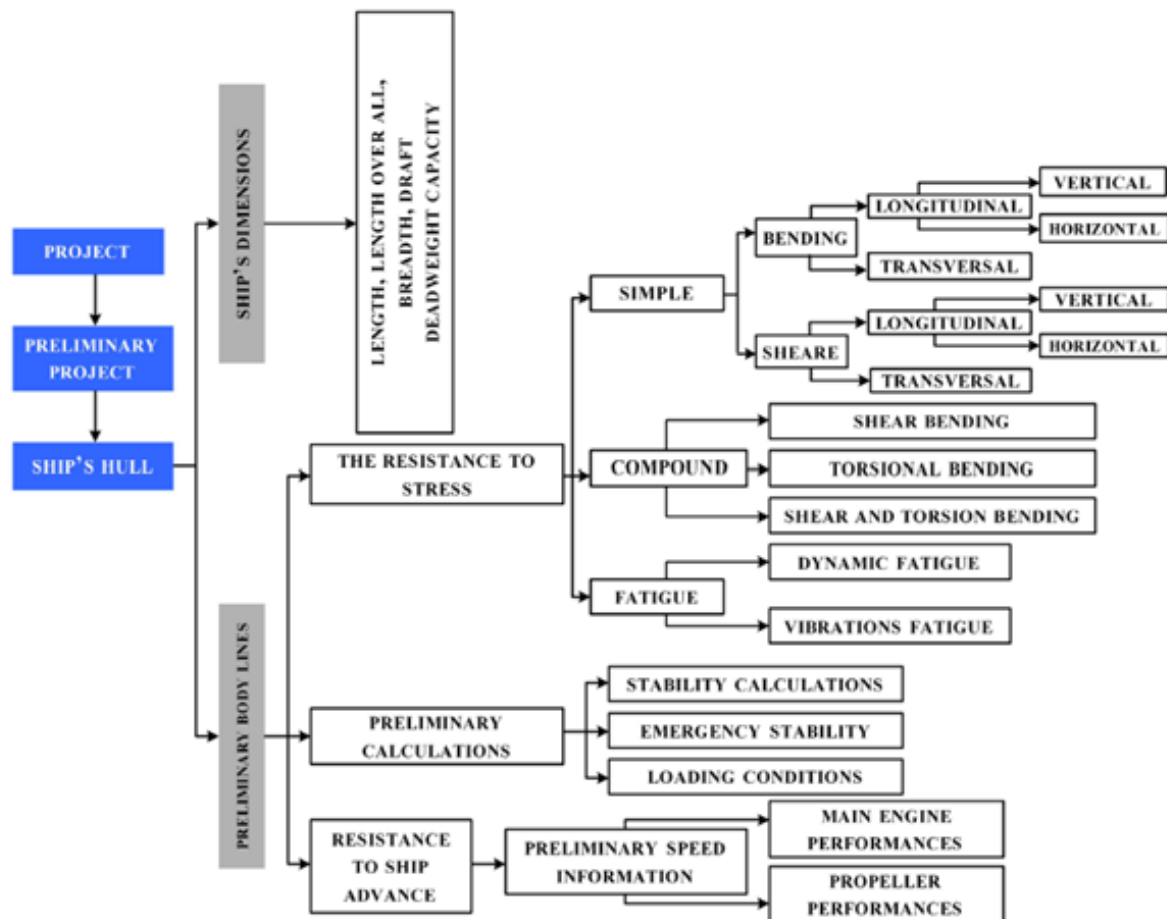
| <u>ESWBS Group</u> | <u>Description</u>                  |
|--------------------|-------------------------------------|
| 000                | General Guidance and Administration |
| 100                | Hull Structure                      |
| 200                | Propulsion Plant                    |
| 300                | Electric Plant                      |
| 400                | Command and Surveillance            |
| 500                | Auxiliary Systems                   |
| 600                | Outfit and Furnishings              |
| 700                | Armament                            |
| 800                | Integration/Engineering             |
| 900                | Ship Assembly and Support Services  |

Figure 15 – An example of SWBS Breakdown [24]

SWBS Breakdown was developed in the 1970s to manage US Navy ship systems. It can be defined up to 900 components. In detailed engineering, various design analyses and evaluations are performed, often concurrently among different teams to manage all the required systems that need to

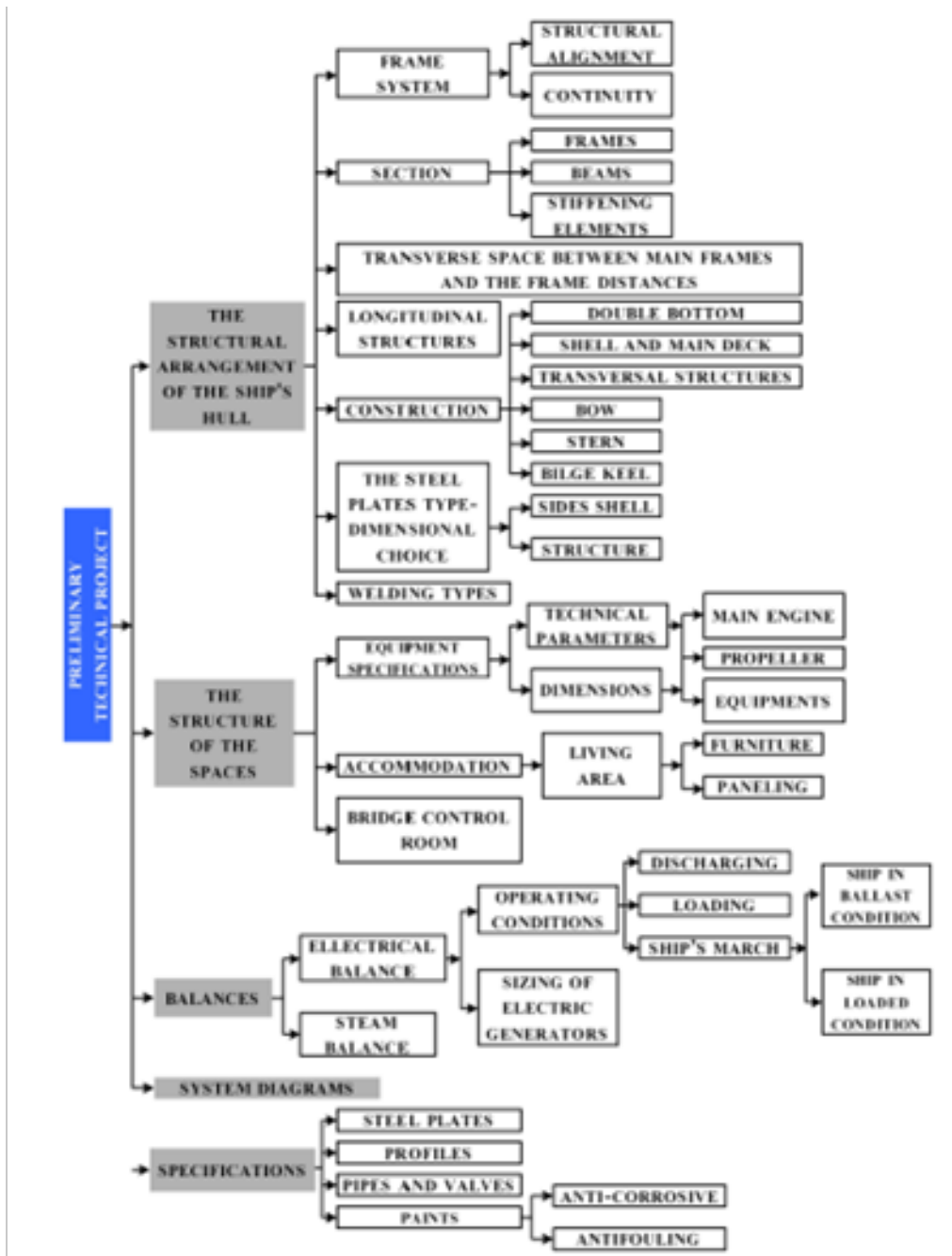
be evaluated. Design work planning and execution at this phase involves the coordination of tasks involved in (a) detailed design definition, (b) design evaluation (quality control and testing), and (c) design compliance (regulatory and specification compliance).

Alternative project task decompositions may exist depending on the scope of the project and depending on a company's documentation standards. For example, basic and detailed projects may have varying degrees of engineering work requirements. A Detailed Project Design package may be applicable for ready-to-build ship, while a Basic package is applicable for a ship design proposal.



## Basic Project Design

Figure 16 - An Example of Basic Project Design [25]



## Detailed Project Design

Figure 17 – An Example of Detailed Project Design [25]

For example, the following timeline and lifecycle incorporates the document approval with the main systems (and task) breakdown from Ulstein as shown in Figure 16 and Figure 18.

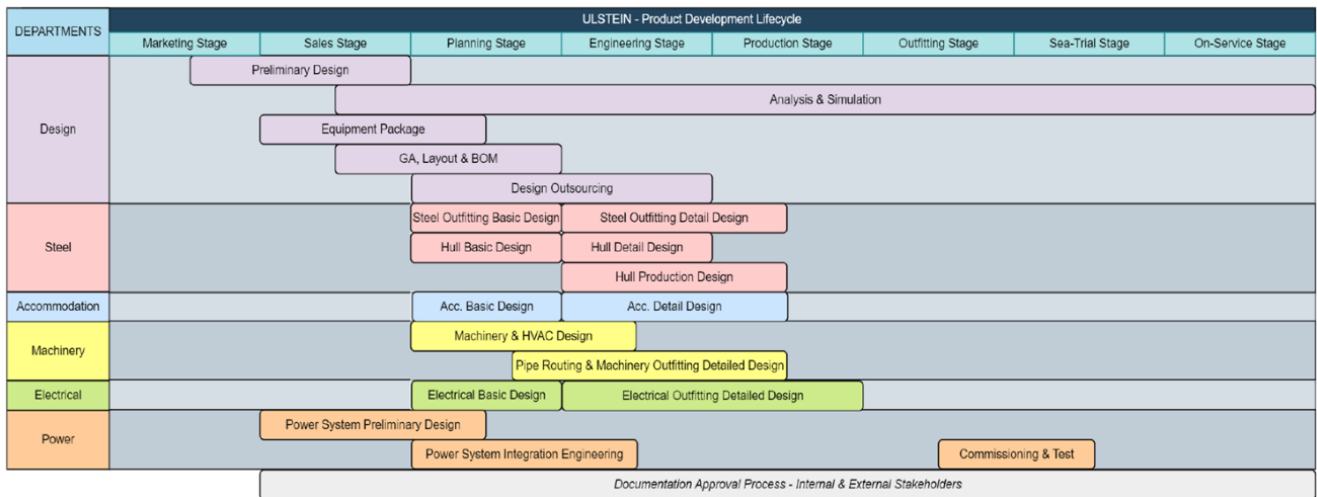


Figure 18 – An Example of the Timeline and Lifecycle of the Ship [26]

Design Evaluation Tasks of the design can involve simulation testing and physical testing – from FEA to towing tank testing. An example of the hydrodynamics tests that should be performed is shown in Figure 19.

|  |  |
|--|--|
| <b>Resistance and Propulsion Tests</b> | <ul style="list-style-type: none"> <li>Determining resistance and propulsion characteristics. It may be important to improve the accuracy of the prediction beyond that estimated using predictive standard series techniques. For some ships, the hull form parameters may be outside of the range of available data and model tests may be particularly important. Appendage details may require investigation.</li> <li>Determining the impact of changes, comparing alternative hull forms, or optimizing the hull for a particular purpose. Selecting final bulbous bow characteristics to suit various operating conditions may require comparative tests.</li> <li>Improving the level of confidence in a powering prediction. This could be desirable for many reasons, including the selection of a specific diesel engine or gas turbine.</li> </ul>                           |
| <b>Propulsor Tests</b>                 | <ul style="list-style-type: none"> <li>Evaluating wake characteristics of the hull to assist in propeller design and optimization.</li> <li>Evaluating alternative propulsors or improving the accuracy of propulsor efficiency predictions.</li> <li>Determining propulsor cavitation or noise characteristics. For some ships where these characteristics are KPPs, such tests may be essential to confirming such performance.</li> </ul>   |
| <b>Maneuvering Tests</b>               | <ul style="list-style-type: none"> <li>Determining the maneuvering characteristics. This may be particularly important for hull forms that have unusual proportions for which prediction techniques are not accurate. Also, ships that conduct alongside operations such as underway replenishment maneuver in very confined areas or have particularly demanding maneuvering requirements. They may require tests where predictions are not accurate or a higher degree of accuracy is required.</li> <li>Evaluating alternative control surfaces relative to maneuvering requirements.</li> </ul>  |
| <b>Ship Motions Tests</b>              | <ul style="list-style-type: none"> <li>Predicting accelerations, periods, and magnitudes of motions. Unusual hull forms or characteristics may require tests to accurately determine the range of accelerations. This could be to assess operating limits, to provide structural or system design information, or to support HSI objectives.</li> <li>Predicting slamming characteristics.</li> </ul>  |
| <b>Special Hydrodynamic Tests</b>      | <ul style="list-style-type: none"> <li>Determining astern powering or stopping characteristics.</li> <li>Flow visualization. This may be needed to align appendages, or for special mission ships, to assist in minimizing hydrodynamic noise.</li> <li>Fin stabilizer alignment.</li> <li>Determination of propeller-induced vibratory forces.</li> <li>Shaft and strut alignment.</li> <li>Topside airflow.</li> <li>Dynamic Stability. The increasing interest in dynamic stability and unusual hull forms may require tests to assess stability characteristics in special conditions.</li> <li>Examining special hydrodynamic phenomena. An example of this might be the behavior of water within a well under specific conditions.</li> <li>Determining structural loads. These may be required for structural design purposes or to investigate operating constraints.</li> </ul> |

Figure 19 – Examples for Hydrodynamics Tests [20]

In addition to technical testing, design compliance, and review are critical to ensure that the ship can get class approval for operations, meet pollution requirements, and satisfy clients' needs. In addition

to the Classification Society’s Approval (Class Approval) upon review, ships may also require additional certificates. Each certificate will have its unique requirements. Regulatory bodies will inspect that the ship is compliant with these requirements. In this phase, the use of a more detailed functional breakdown or a detailed (3-digit) ship work breakdown is used. As [27] describes, using functional systems is very practical in the contract phase of shipbuilding. For example, passenger ships in the UK will require the following certification: Passenger Ship Safety Certificate, International or Domestic Safety Management Certificate, MCA approval for manning, MCA approval for passenger counting and recording, if over 24m but under 400GT a Declaration on Anti-Fouling Systems, International Anti-Fouling Certificate (instead of a Declaration) if 400GT or over, if carrying Dangerous Goods and built after 1 September 1984, a Document of Compliance for the Carriage of Dangerous Goods, and if over 1000 GT, a Certificate of Insurance or Other Financial Security in Respect of Civil Liability for Bunker Oil Pollution Damage [28]. Complexity in detailed design is a mix of technical complexity and the complications of managerial coordination as shown in Figure 20.

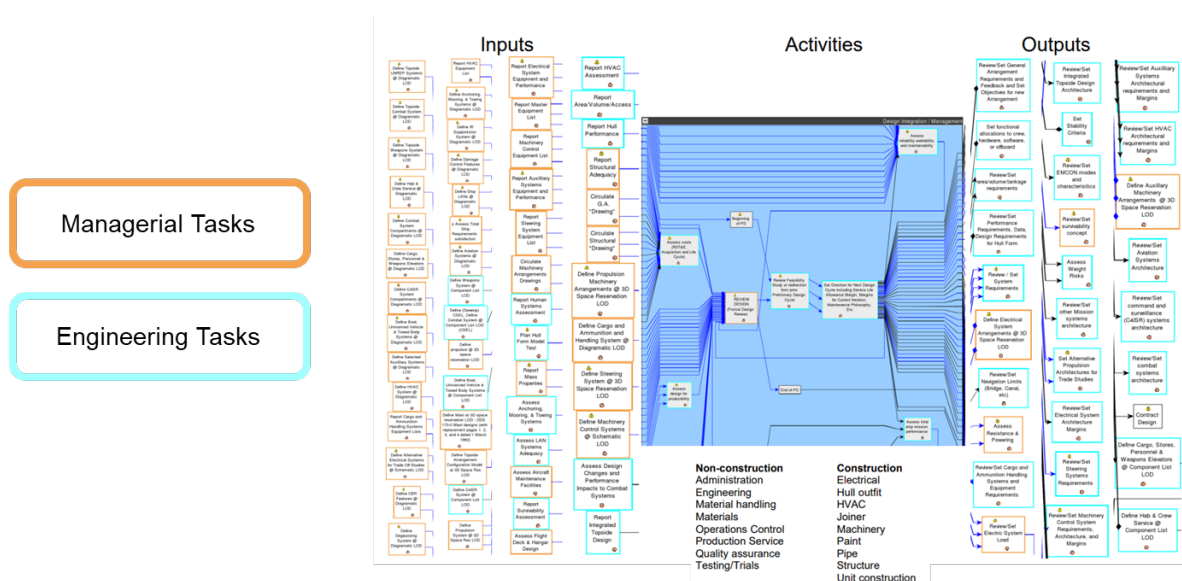


Figure 20 – An Example of Complexity in Detailed Design [20]

When class work is approved, the designers can start preparing production drawings. During this phase, the intent is focused on converting the detailed designs into physical realization in a shipyard, which entails converging the shipyard’s facilities, resources, and processes into the production process. In this phase, work is broken into a product work breakdown structure (PWBS) methodology which can incorporate the ship or product data with workplace, workers, and time. When a PWBS system is successfully integrated with these production drawings, this allows for a noticeably clear breakdown of jobs and interim product development [27]. This phase is also focused on converting the system’s data into block and zone orientation. The phase is quite sensitive to the planning being done by the shipyard and successful integration of construction plans and production deliverables is essential to reduce bottlenecks. The output of the phase involves a more detailed virtual prototype reflecting the block and zone arrangement [29] and work instructions that can be conducted in the yard. The construction process of a vessel is heavily dependent on the build and manufacturing strategy used by the shipyard and is focused on conducting the work instructions generated in the previous step or concurrently. These strategies are reflected by the available facilities and technology within the yard and will be described in more detail in the following sections. For example, some yards dedicated to building the complete ship, or ‘integrated yards,’ are also likely to follow a more historical

Stick Building approach [30] where all outfitting work is done onboard after the hull assembly is complete. On the other hand, yards that are focused on either the hull or outfitting would follow a more modern modular method where ships are divided into blocks, which may or may not be outfitted, and then assembled. Currently, this is the most common and current shipbuilding approach. Regardless of the type of yard and building strategy, the ship construction falls within the key milestones of keel laying and launching and involves steel structural construction including blasting and painting, outfitting (at different degrees and locations in a yard or different yards), and erection.

### 2.3.3 Construction

The construction process of a vessel is heavily dependent on the build and manufacturing strategy used by the shipyard and is focused on conducting the work instructions generated in the previous step or concurrently. These strategies are reflected by the available facilities and technology within the yard and will be described in more detail in the following sections. For example, some yards dedicated to building the complete ship, or 'integrated yards,' are also likely to follow a more historical Stick Building approach [30] where all outfitting work is done onboard after the hull assembly is complete. On the other hand, yards that are focused on either the hull or outfitting would follow a more modern modular method where ships are divided into blocks, which may or may not be outfitted, and then assembled. Currently, this is the most common and current shipbuilding approach. Regardless of the type of yard and building strategy, the ship construction falls within the key milestones of keel laying and launching and involves steel structural construction including blasting and painting, outfitting (at different degrees and locations in a yard or different yards), and erection. However, up to this stage, most designs are conducted in 2D drawings due to delivery schedules and changes. When a ship design is ready for construction, intermediary steps related to ship design contracting follow Figure 21.

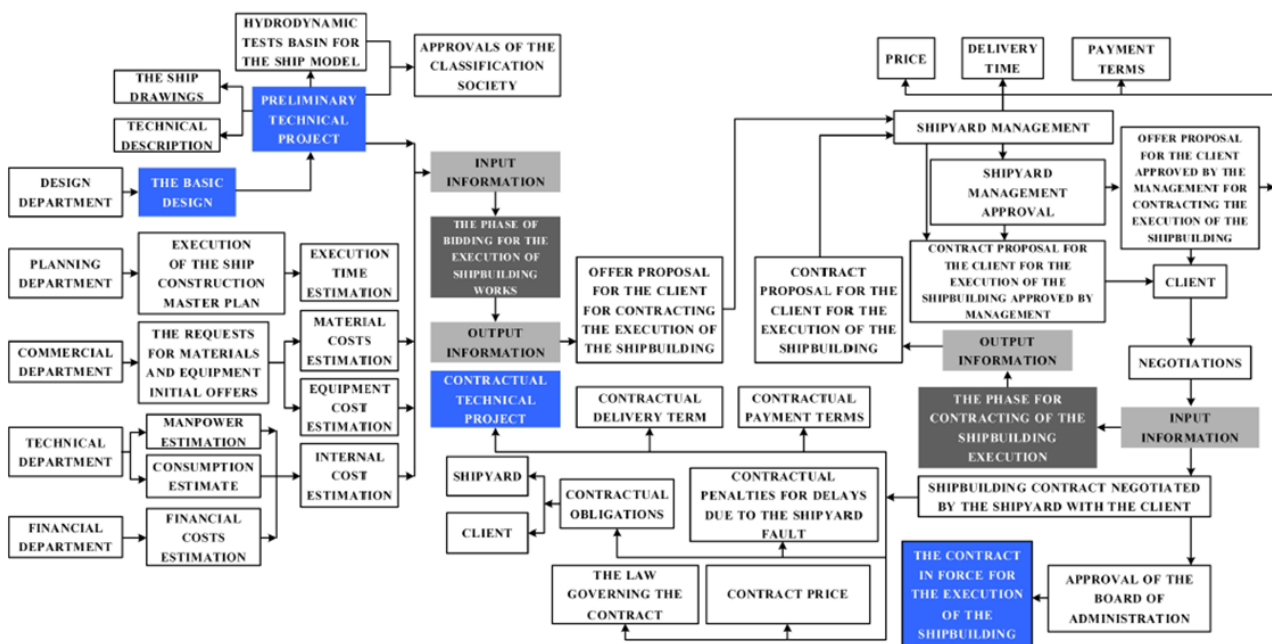
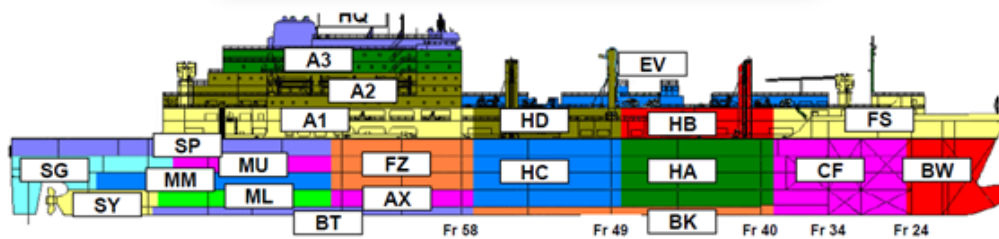


Figure 21 - Intermediary Steps Related to Ship Design Contracting [25]

When a contract is won, the ship design and design outputs are converted so they are production-ready. This phase is often called ‘transitional design’ which involves the conversion of the functional ship outputs into Block and or Zone orientation based on the facilities available in the yard. The ship’s virtual prototype is also often ready for the development of production drawings. Zones are developed for ease of construction. These are areas of sea-frame that are in physical proximity, and that serve similar or bundled functions and services. Some yards will use the term superblock or block assemblies instead of zones.

## Zone Breakdown



| Type  | Zone | Description                   | Type  | Zone | Description             |
|-------|------|-------------------------------|-------|------|-------------------------|
| Cargo | BK   | Bilge Keel & Double Bottom    | Mach  | SG   | Steering Gear           |
| Cargo | HA   | Multipurpose Hold #1          | Cargo | FZ   | Freeze/Chill            |
| Cargo | HC   | Multipurpose Hold #2          | Cargo | CF   | Cargo Fuel Tanks        |
| Mach  | AX   | Auxiliary Machinery Room      | Accom | A3   | Accommodations Upper    |
| Accom | A1   | Accommodations Lower          | Cargo | FS   | Foc'sle                 |
| Mach  | BT   | Machinery Bilge & Waste Tanks | Cargo | HD   | Topsides Hold 2         |
| Mach  | MU   | Machinery Upper               | Cargo | BW   | Bow                     |
| Mach  | ML   | Machinery Lower               | Cargo | HB   | Topsides Hold 1         |
| Mach  | MM   | Machinery Mid                 | Cargo | SP   | Specialty Cargo         |
| Mach  | SY   | Shaft Alley                   | Accom | HQ   | Bridge & Communications |
| Accom | A2   | Accommodations Mid            | Cargo | EV   | Elevator Houses         |

22 Total Zones { 7- Machinery, 11- Cargo, 4- Accom } – 3 IPT Areas

Source: T-AKE program, Spring 2005

Figure 22 – An Example of Zone Breakdown in Shipbuilding [24]

Block assemblies, super blocks, and or zones are made up of systems, steel blocks, and their respective sub-divisions (e.g., a structural block or outfit unit, a subassembly of either, and ultimately, a part or component). Figure 23 shows an example of modular shipbuilding by block assembly and pre-outfitting.

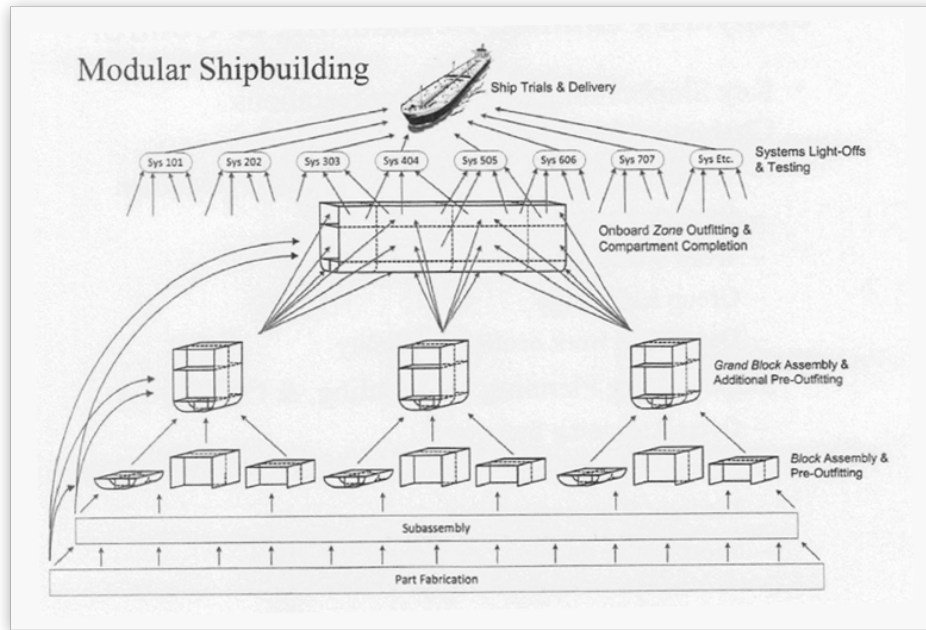


Figure 23 – An Example of Modular Shipbuilding [29]

To facilitate construction, work is organized according to group-technology based process lanes. Shopfloor work is grouped in terms of production characteristics and processes. Cellular work centers or process lanes become easier to establish, consolidating equipment and workers with similar skills. Task packages are therefore reorganized or developed from zone-based data to suit finer divisions of labor as shown in Figure 24.

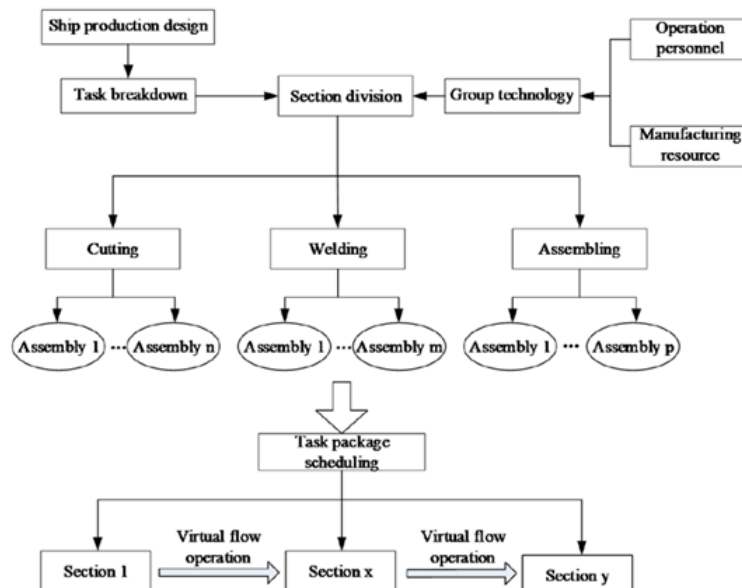


Figure 24 - Shopfloor Planning [31]

Work and task description documents can increase substantially during the production phase, to incorporate all the technicians in the shopfloor. Demand and work content variability become tricky to coordinate. For shipyards that have multiple projects, this degree of scheduling inflates rapidly. A high

understanding of utilization and workload leveling, advanced planning, and communication are key. Figure 25 shows an activity map for the simultaneous scheduling of a shipyard.

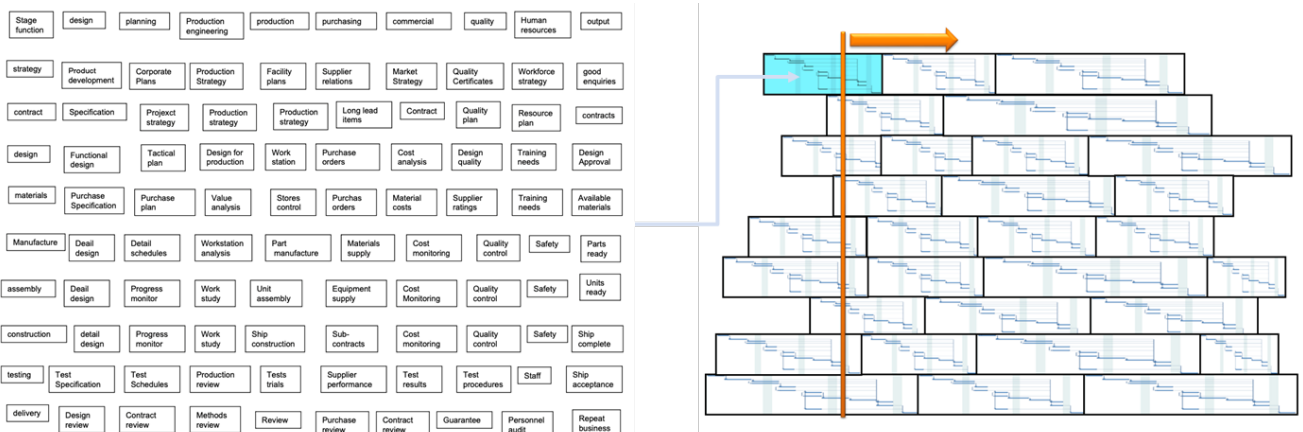


Figure 25 – 10x10 Activity Map for Ship Design and Shipbuilding and Simultaneous Scheduling (left) [32] and (right) [33]

In ship construction, the ship is mainly viewed as a combination of structure and outfit. A structure is the sum of a hull form and a superstructure and includes hull shell plating, decks, stiffeners, rudders, castings, etc. It is hierarchical and flow-oriented. Outfitting includes piping & hull attachment fittings, furnishings, cargo handling gear, cargo piping, electrical generation and distribution, main propulsion machinery, etc. Contrary, it is heterogenous, and not very flow-oriented. Due to the heterogeneity of outfitting parts, outfitting work is often completed at different times leading to various outfitting phases during construction. In the case of on-block outfitting, machinery, and generators are already outfitted on the steel or structural block. It has better working conditions and access, with downsides in weight for assembly. In the case of on-board outfitting (dock or quay outfitting), engine installed after ship blocks have been assembled. It can allow for concurrent design and production if there is delay in installation, but much more costly to install.

The ship construction process becomes highly focused on flow and the coordination of materials, parts, and labor. The focus question is: How can we incorporate more hierarchical practices to make material flow, labor coordination and planning more efficient and less costly? Economies of scale (EoS) are critical to consider. Shipyards need to understand how EoS affects their business and how they can strategically keep costs low by increasing volume or scale. Based on EoS, it is smarter to spread capital and non-manufacturing costs and focus on specialized labor and capital. These strategies are reflected in the shipyard design.

As of late it is much more expensive to build the hull in Europe due to high labor costs and throughput costs. For example, in 2013, European yards had a lower productivity average compared to shipyards in Japan and Korea of a shipbuilding company. These business & production factors have a heavy influence on the shipbuilding and build strategy. The build strategy is a plan for design, materials management, production, and testing in the shipyard. Semini et al. [17] conducted studies on the different strategies employed in Europe, particularly in Norway. They found that although there are still some shipyards that fully construct a ship locally, the most common strategies include offshoring the entire hull construction and or blocks abroad.

A ship production workflow involves a hierarchical materials and components flow as outlined by [30] and [35]. When it comes to the materials flow, there are a few governing philosophies that are applied such as the principles of one-piece flow [36] and reduction of excessive movements [37]. However, these construction best practices may not always happen seamlessly, especially when there is a lack of technology or lack of proper coordination in the yard. The phase of ship construction includes pre-processing, fabrication, assembly, precedence outfitting, painting, precedence block erection, block erection, outfitting, etc. These processes occur in a very complex pattern over a long period [38].

Production and materials coordination is implemented in the form of medium- and short-term planning. Medium-term planning involves the creation of an 'Integrated Master Plan' which provides a coordination of the projects with in-house facilities in the yard. A master plan may also be designed for a particular ship. A ship's master plan also called the master program, master schedule, main schedule, or milestone plan, contains key dates, such as contract signing, the start of steel cutting, keel laying, launch, and delivery ([18], [32]). Planning that comes down to the day-to-day execution of this plan falls within short-term planning. Short-term planning is also concerned with 'shop floor planning' where work orders and task packages are generated, issued to be scheduled by a planner, and monitored for implementation until completion [30].

Due to the heavy offshoring that is happening in Europe and the fact that not a lot of yards are integrated yards, this workflow is more fragmented leading to an unavoidable complexity that comes with stakeholders spread in different locations that have their standards, processes, and communication differences. In addition, the various gates between lanes show where there is heavy communication or interfacing between the different groups. The processes defined during ship production until delivery are taken from the materials flow chart created by [35], while the headers for the different lifecycles are derived from the lifecycle phases as described by [17] where steel construction and outfitting are presented concurrently. In practice, these 2 stages may overlap or happen in series, increasing overall time in production pre-assembly.

As can be seen in Figure 26, Strategy I where a complete ship design and production process is implemented has the least number of communication gates whereas the rest of the strategies have to communicate not only with external marine equipment suppliers but one or more shipyards that perform specific construction functions. The gates presented in the figure are also further simplified, as in reality, the main European design firm is also responsible for quality control and therefore liaises with all the different parties throughout the lifecycle of the vessel. In addition, where shipyards perform dedicated steel or outfitting work, concerns are not only limited to the integration and conversion of design instructions at the start but also to the physical integration of material/equipment components and ship blocks in the European yard. When reality does not match expectations, high costs and time are required for those discrepancies. There are also added technical risks when it comes to the management of data. Due to differences in process or standards across different yards, data needs to be converted and rehashed multiple times leading to version control issues. Finally, with greater moving parts across different stakeholders, the production process is more susceptible to schedule and scope creep. The following figure summarizes the integration concerns that each strategy may face.

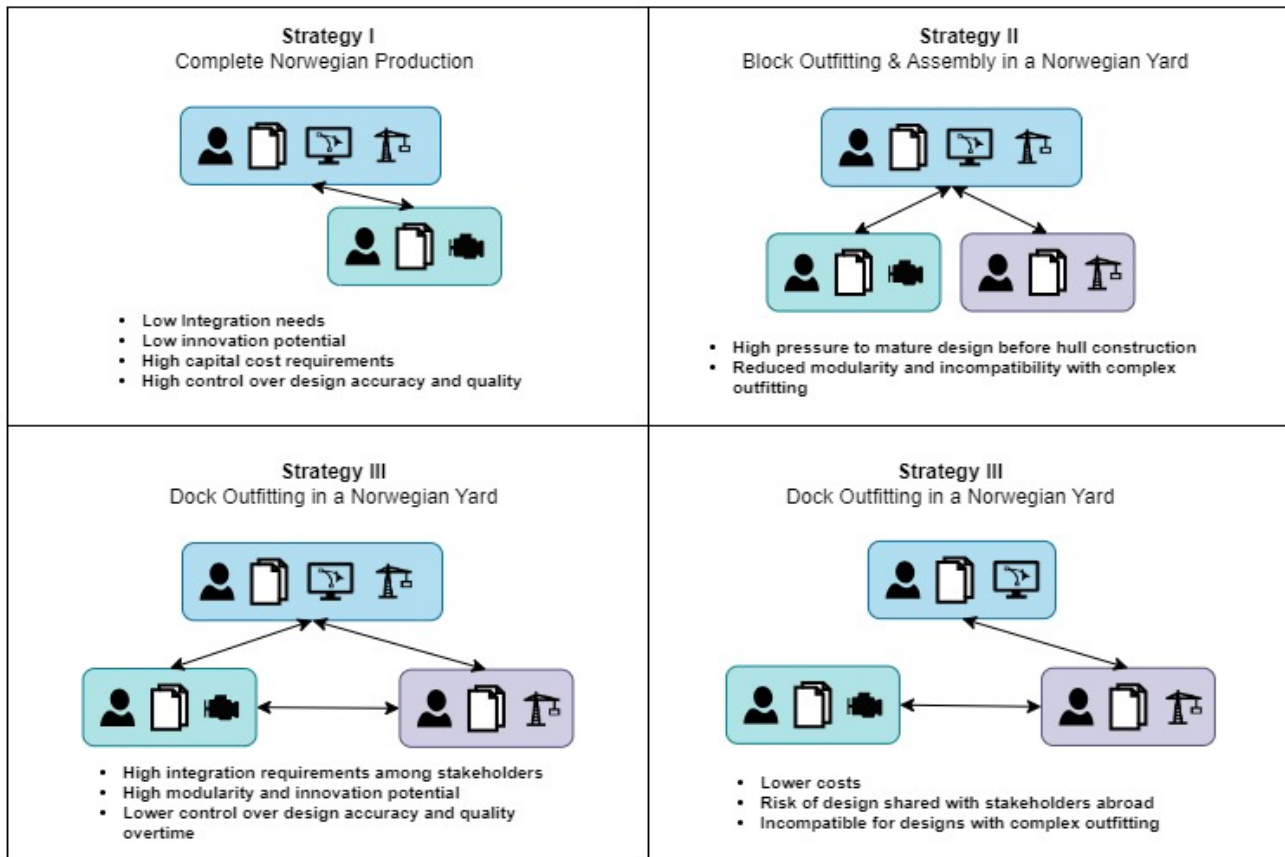


Figure 26 - Integration Risks for Different Strategies

Each strategy faces its own risk, both in data and systems integration, due to the variability in the stakeholders, interactions, and information exchange. Every yard will have unique facets of their production, aligning and deviating from these four strategies. When the vessel is launched and onboard outfitting is complete, testing and sea trials are performed to ensure that the vessel can float and is operational as expected.

There are more than a few people involved there are more than a few entities or persons involved in the workflow. As described by [1], there could also be more than one or more yards involved. The following figure for example provides the involvement of different entities and persons in the workshop owing to the complex nature of managing and maximizing the available resources.

## 2.4. Multi-domain Taxonomy

There are a few key features in ship design and shipbuilding that affect the information systems that are used in design firms and yards, as noted in the previous section. Figure 27 shows the design and building orientation from 1960s to 1990s.

| <b>Business function</b> | <b>Mid-1960s</b> | <b>Mid-1990s</b>                |
|--------------------------|------------------|---------------------------------|
| Ship specification       | System           | System                          |
| Ship design              | System           | Varies with zone, system, other |
| Cost estimation          | System           | Varies                          |
| Budgeting                | System           | Product and process             |
| Planning                 | System           | Product and process             |
| Operations               | System / trade   | Varies with trade, area, skill  |

Figure 27 – Design and Building Orientation from 1960s to 1990s [40]

As the figure shows, the ship design had the following key features.

- Information and data management priorities vary in every stage of the lifecycle
- Functional Breakdown structures are common in design while Physical Block and Zone Breakdown structures are common in construction
- Challenging exchange and retention of information across each phase
- Rapid increase in data generation from design definition, evaluation, and testing

Unfortunately, these features have not changed drastically since the 1990s. The reliance on legacy tools increases the risks of incurring high technical debt in ship design software. As a basis for a plan to improve it, we perform a decomposition of work. The definition of a standard ‘work element’ has always been a challenge in ship design. Historically, the work element is based on functional breakdowns, but this has led to constraints in incorporating scheduling and planning data. As echoed by NAVSEA [20] and by Pal [24], breaking down a ship by functions greatly limits the incorporation of planning data, BOM, BOP, and connection with the data format.

There is still missing information with the definition of a ship ‘Work Element’, despite the incorporation of process, planning, and work type data in PWBS. Tedious conversions, revision control, and manual incorporation of 2D/3D files are still the norm today. Figure 28 shows an example of file flow of ship design and shipbuilding.

A common approach in systems engineering to the definition of work involves the understanding that these work elements evolve throughout the ship lifecycle. The V-model is one way to view the evolution of the work element definition. It incorporates a functional ship concept with physical materials and realization as shown in Figure 29.

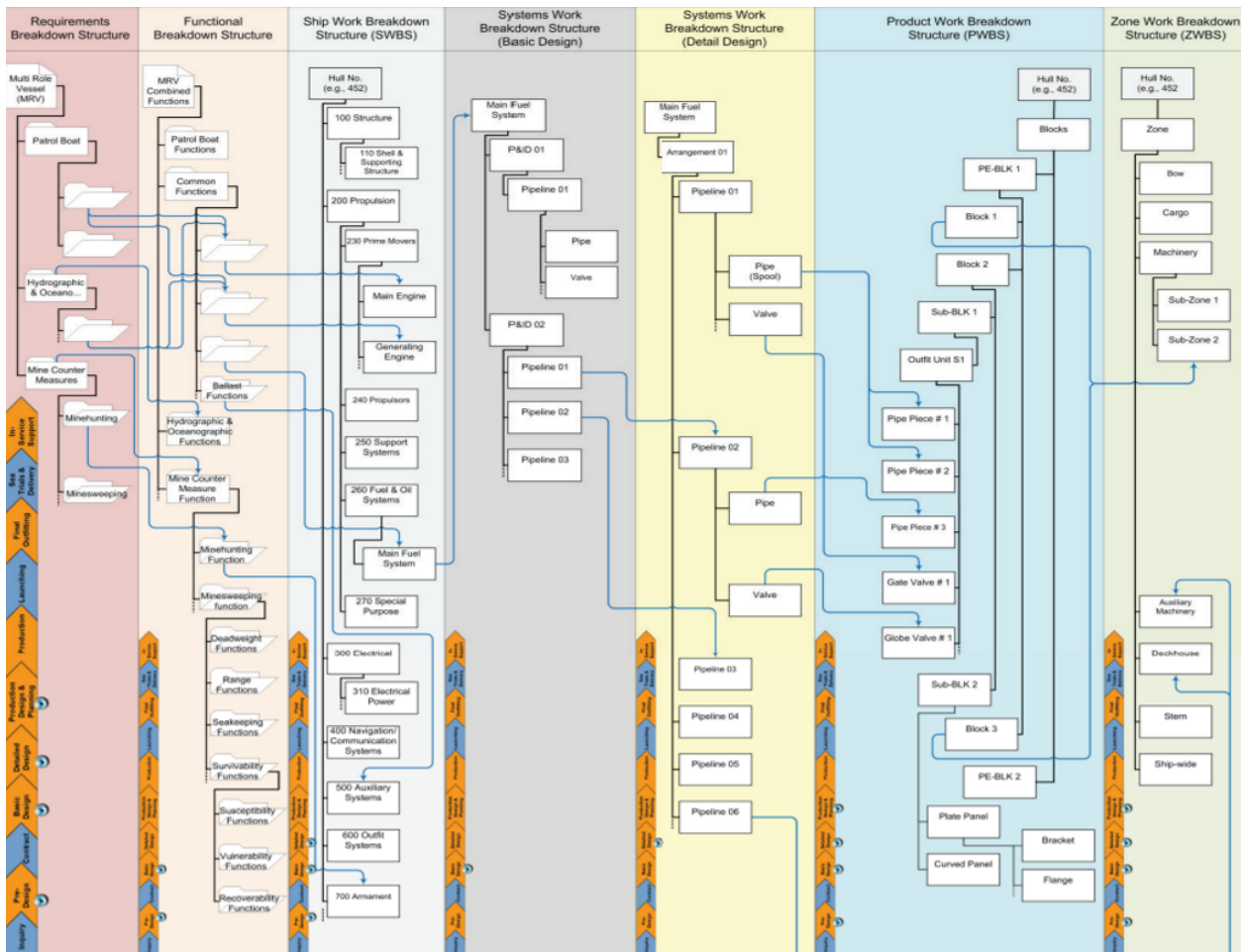
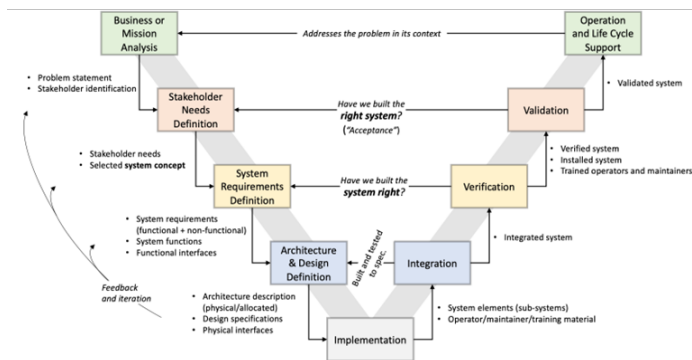


Figure 28 – An Example of 2D/3D File-Flow of Ship Design and Shipbuilding [41]

### Systems Engineering V-model



### V-model applied to Ship Design and Shipbuilding

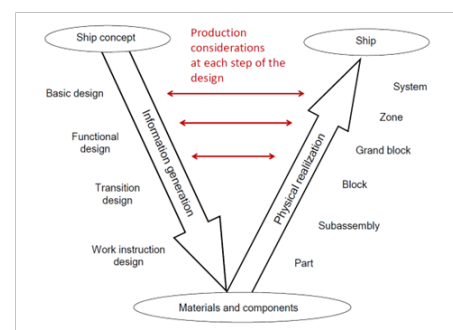


Figure 29 – The V-model Applied to Ship Design and Shipbuilding [40]

Unfortunately, this symmetrical assumption of the process is often incomplete and not realistic. Ship design and construction process are not linear and are more stochastic and complex. The simplification of the v-model may not apply to a ship due to the following features adapted from [42]. The ship is a highly-integrated structure, operating in the boundary between two fluids, multi-dimensional, partly non-monetary performance evaluation, high cost of error, shallow knowledge

structure, strong domain tradition, strict time, resource constraints on the design process, and predominantly 'one-of-a-kind' and 'engineering-to-order' solutions. An alternative approach to systems design is a process of mapping between design domains ([43], [44], [45]).

Outside functional and physical domains, other studies extend to include team, workplace, and workflow data for a more complete virtual prototyping of a shipyard. Network Maps are developed in these studies to understand ship data connections between these domains as shown in Figure 30.

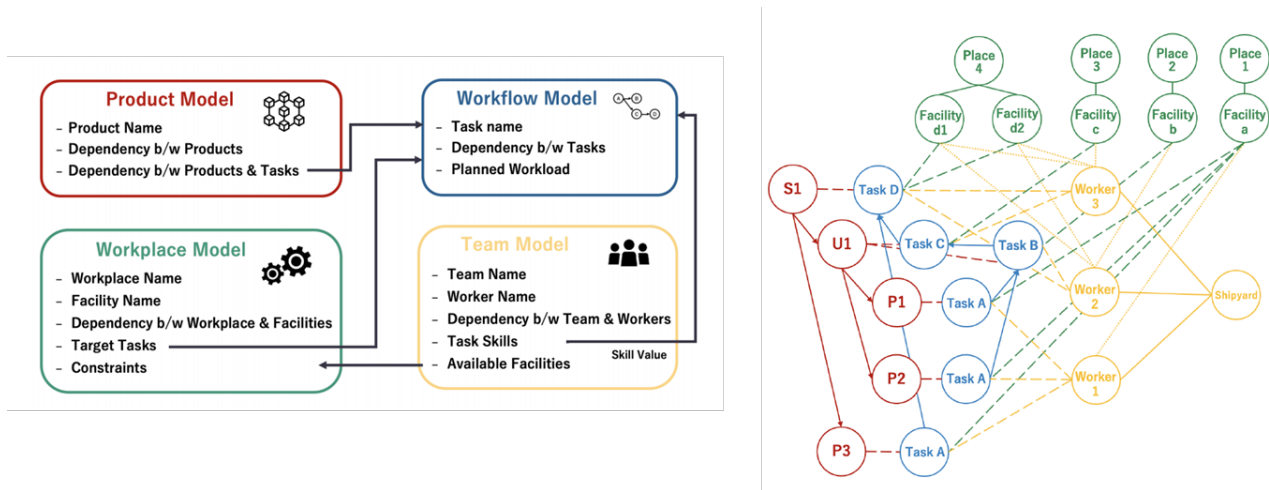


Figure 30 – Network Map to Understand Ship Data Connections Between Domains [46]

The incorporation of additional planning data (including workplace, workflow, and people) broadens the concept of a ship digital twin to a more temporal aspect of the entire ship digital thread. The digital thread enables end-to-end connection with digital models and twins across the entire lifecycle.

In addition to the different layers that ship designers and yards need to consider, various data domains, structures, and types must also be accounted for. As introduced in Figure 31, these data domains are not bound to a particular lifecycle phase or layer. Instead, they are dynamically used by companies and yards as a function of experience, 3rd party choices, business practices, and personnel preferences.

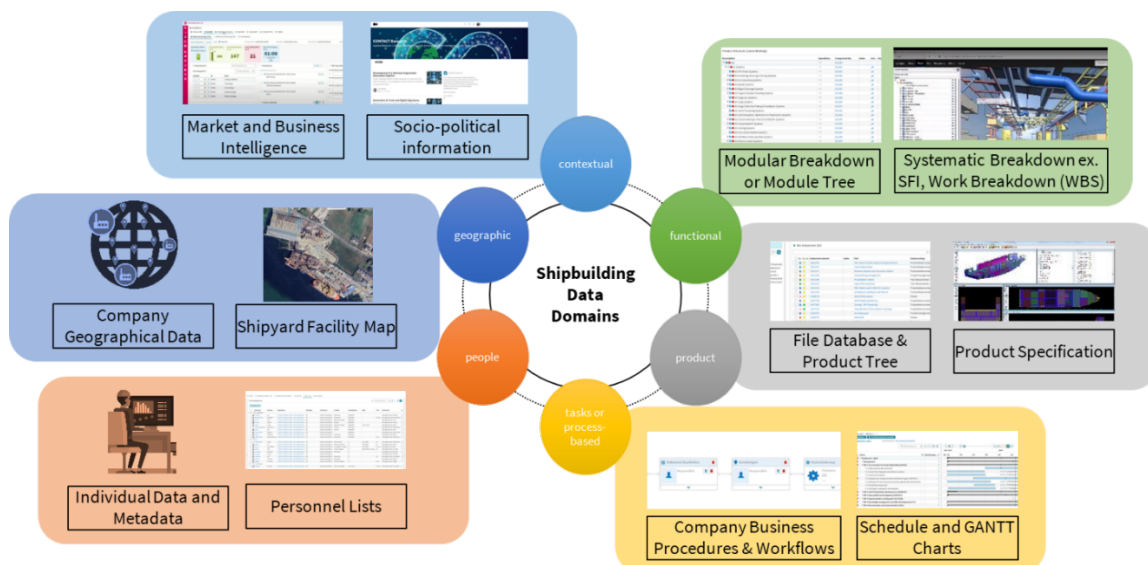


Figure 31 - Data Domains in Ship Design and Shipbuilding (Internal data of SEUS from CADMATIC)

- Functional Domain

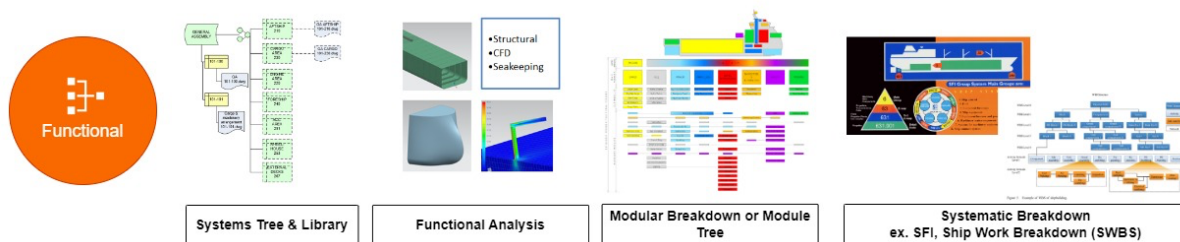


Figure 32 - Functional Domain Interpretation in Ship Design and Shipbuilding (Internal data of SEUS from NTNU)

Functional data is information that deals with the organization of project tasks and components. A modular breakdown or module tree structures the project into manageable sections or modules. Systematic breakdown methods, such as the Standard Form of Identification (SFI) or Work Breakdown Structure (WBS), further decompose the project into smaller, more manageable tasks. This systematic approach helps with project planning, scheduling, and execution.

The 'Ship Work Breakdown structure' is one of the earliest functional breakdown structures for a ship historically developed with the Program Evaluation and Review Technique by the US Department of Defense (DoD). This method, along with other methods such as the Program WBS, Contract WBS, Ship Work Breakdown Structure (SWBS), and SFI Group SWBS uses system-oriented elements to create a WBS that can be used for estimating man hours and cost up to a level of accuracy [47]. In terms of work coordination, however, it is unrealistic to control results from huge work packages and ineffective to control material, man-hours, and schedules. The sole focus on the systems-oriented structure will make it difficult to arrange other construction management such as the procurement of materials or fabricating parts to meet the system's basis of construction [47]. The classification happens at 3 levels and is also like programs like SFI.

Work breakdown structure (WBS) can help shipbuilding projects decompose work oriented by deliverables achievements (products, information, and services, etc.) [47] and an appropriate WBS is a basis for improving the efficiency of the shipbuilding industry. To support planning better and more effectively, management, coordination, etc., some scholars have studied information integration on WBS. However, the design and decomposition of WBS are based on the structure and logic order of a project, so tasks are usually split only once by the WBS method and are no longer adjusted ([48], [49])

In addition to the conventional representation of the ship breakdown, other standards have also been used such as the SFI Coding and Classification System first released in 1972 as the result of a research project undertaken by the Ship Research Institute of Norway (SFI: Skipsteknisk Forskningsinstitutt). Depending on the mission requirements of the vessel as well, ship designers may opt for a modular breakdown or custom systems hierarchy.

- Product Domain

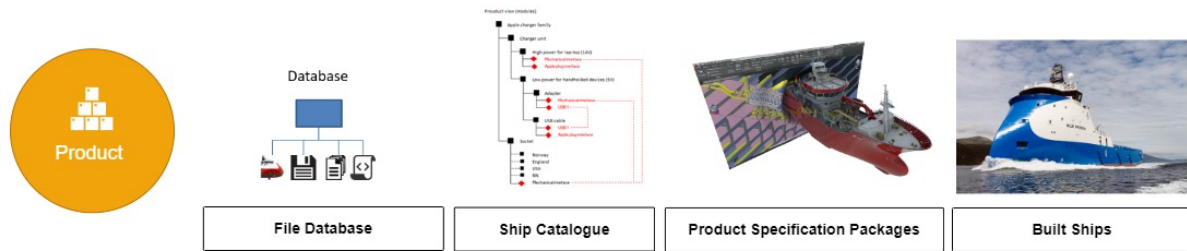


Figure 33 - Product Domain Interpretation in Ship Design and Shipbuilding (Internal data of SEUS from NTNU)

This domain encompasses the management of data related to the form or physical realization of ship parts that perform specific functions [50]. The file database and product tree organize all the files and documents associated with the product, ensuring easy access and retrieval. Product specifications detail the technical requirements and standards that the product must meet. Proper management of product data ensures consistency, quality, and compliance with specifications.

- Task (or Process) Domain

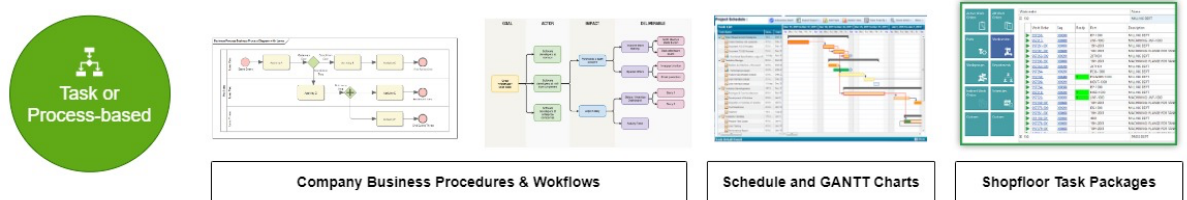


Figure 34 - Task Domain Interpretation in Ship Design and Shipbuilding (Internal data of SEUS from NTNU)

This domain focuses on the processes and workflows that drive the project including administrative tasks (planning and scheduling) and technical tasks. Due to the high complexity of a ship, multiple administrative and technical processes govern the completion of a ship's design and construction [43]. Company business procedures and workflows outline the standard operating procedures and processes that must be followed. Schedules and Gantt charts are tools used for planning and tracking project timelines, ensuring that tasks are completed on time. This domain is essential for maintaining project control and ensuring timely delivery.

- People (Human) Domain

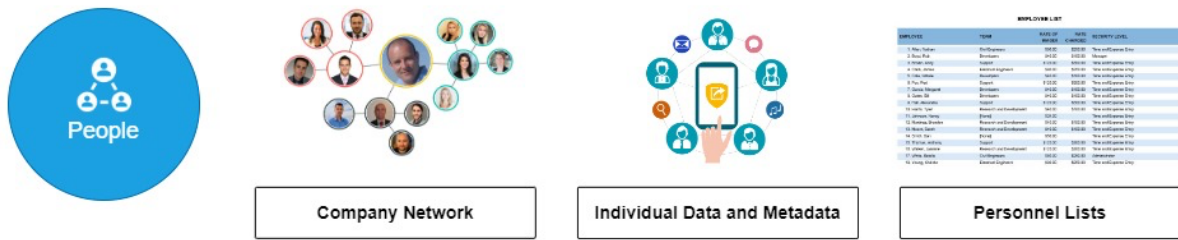


Figure 35 - People Domain Interpretation in Ship Design and Shipbuilding (Internal data of SEUS from NTNU)

People data is information related to the persons associated with executing tasks and various ship design and shipbuilding activities. It includes individual data and metadata, which provide information on employees' roles, skills, and contact details. Personnel lists are used for workforce planning, ensuring that the right people with the necessary skills are assigned to the appropriate tasks. Effective management of human resources is vital for project success.

- Geographic Domain



Figure 36 - Geographic Domain Interpretation in Ship Design and Shipbuilding (Internal data of SEUS from NTNU)

This domain focuses on the geographical aspects of the location of tangible ship assets and material or the shipyard and its facilities. It includes data on the location of company assets, infrastructure, and operational sites. The shipyard facility map is a critical component, providing a detailed layout of the shipyard, which is essential for planning and logistics. Understanding the geographic context helps in optimizing operations and ensuring efficient use of resources. Geospatial data is also critical during ship operations as the Automatic Identification Systems (AIS) monitor and track a ship's position for global fleet traffic management [51].

- Contextual Domain

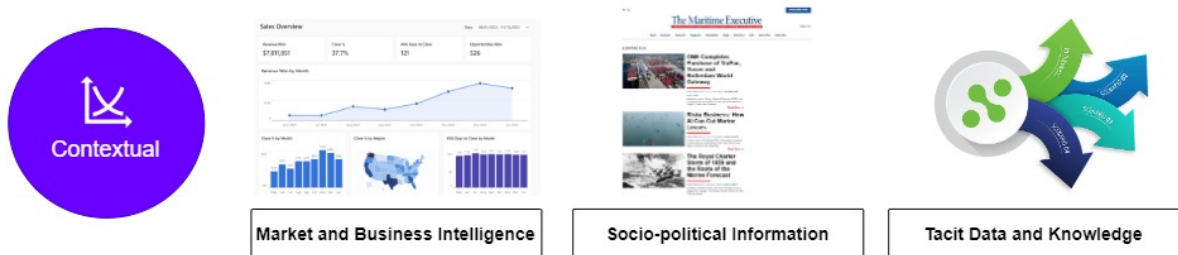


Figure 37 - Contextual Domain Interpretation in Ship Design and Shipbuilding (Internal data of SEUS from NTNU)

This domain involves gathering and analyzing data related to the market, business environment, and socio-political factors. In the shipbuilding industry, uncertainties in multiple dimensions, from business market to vessel behavior, are ubiquitous [52]. This information is crucial for making informed decisions about project viability, market trends, and regulatory compliance. Market intelligence includes data on industry trends, competitor analysis, and economic forecasts. Socio-political information covers political stability, regulations, and policies that could impact the project.

- Domain connection

Unfortunately, the integration of these domains faces 2 main challenges. Firstly, domains are used concurrently across various stages of the entire lifecycle. And secondly, these domains are exchanged across various stakeholders. These domains not only differ in contents and formats but also in their purpose and ownership. Integration solutions must also consider whether the information gathered is generated - from external third parties, or proprietary sources. Figure 38 shows where the information for each domain was generated.

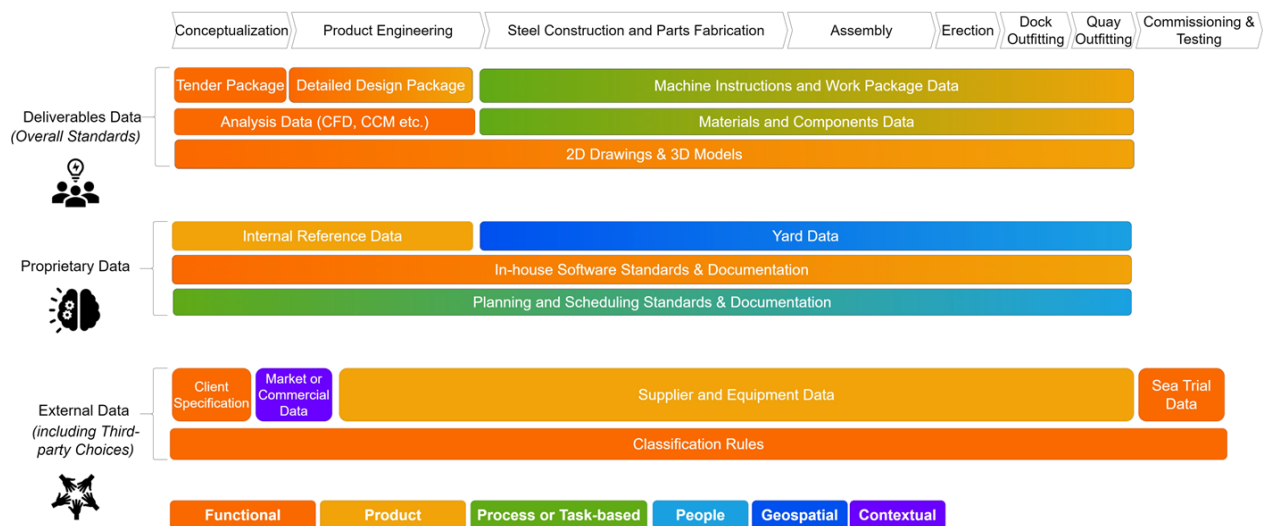


Figure 38 – Where the Information is Generated (Internal data of SEUS from NTNU)

Third-party sources or external parties may involve propeller suppliers, external designers, and classification societies, among others. How can we properly integrate the standards used by different offshored yards, geographically disparate design offices, and contractors? There are plenty of data risks that come hand in hand with the multi-organization happening across the entire lifecycle. These data risks include information theft and design reproduction.

## 2.5. The Ship Design and Shipbuilding Toolbox

Historically, ship design and construction have been heavily reliant on design and modeling tools. In the 1950s to 1970s, CAD/CAE/CAM systems for ship design were extremely popular, and developments in bespoke software solutions for naval architects happened at a rapid rate as shown in Figure 39.



| <i>Year</i> | <i>Hardware</i>   | <i>Software</i>   | <i>End Users</i>                     |
|-------------|---|---|--------------------------------------|
| 1972–78     | Big computing centers, Main frames, Punched cards and alphanumeric terminals                | Independent programs, Sequential files, Batch processes                                 | Big shipyards                        |
| 1979–86     | Medium computing centers, Midi/Mini computers, Alphanumeric terminals and graphic terminals | Integrated programs, Medium level independent databases, Interactive processes          | Big and mid-size shipyards           |
| 1987–94     | Local area networks, Workstations, X-terminals, PCs   | Fully integrated programs, Single database, Interactive graphic processes, Open systems | Big, mid-size and small shipyards    |
| 1995–03     | Remote networks, PCs, Workstations, Parallel processors                                     | Windows environment, Object oriented programming, Improved inter-program data exchange  | All sizes of shipyards, Design firms |

*Figure 39 – The History of Ship Design and Modeling Tools [53]*

Since the 1980s, CAD (Computer Aided Design) and CAE (Computer Aided Engineering) solutions for ship design have been continuously developed and used to assist with specialized modeling and analysis tasks.

| <b>Program Name</b> | <b>Capability</b>   |
|---------------------|---|
| NavCAD              | Resistance and power prediction                                     |
| GHS                 | Hydrostatics, stability, longitudinal strength                      |
| MAESTRO             | Structural design and optimization                                  |
| NASTRAN             | Finite element analysis (FEA)                                       |
| SafeHull            | FEA for yielding, buckling, and fatigue strength of ship structures |
| ShipWeight          | Weight and center of gravity estimation                             |

*Figure 40 – Capabilities of Programs for Ship Design in the 1980s [53]*

Typically, ship design CAD capabilities include hull design, deck and bulkheads definition, compartmentalization, profiles and arrangements, distributed systems, drawings, engineering analysis, and early stage design. Ship design CAE capabilities include: Pipe Thermal Expansion, Pipe and Pressure Flow, Hydrostatics and Stability, Volumes and Cargo Capacity, Loading Conditions, Speed/Power, Plate Bending, Electrical Loading, Weights and Centers, Structure, Maneuvering and Control, Proper, HVAC, Launching, Seakeeping, Noise Analysis

CSM/CAM (Computer-Aided Synthesis Modeling/Computer-Aided Manufacturing) applications have also been in use for steel and parts fabrication, and for ship assembly. Typical ship design CAM functions are as accounting for weld shrinkage, dimension control, an interface between product model and robots, robotic programming, production management support, lifting planning, paint design and monitoring, part coding and hierarchy, nesting, flat and profile forming, pipe bending, and cable length.

Testing methodologies since the 1960s have greatly improved from model hulls faired and fabricated manually to CNC-machined hull forms. Given the high reliance on computer-aided tools, Information Integration has been critical in the industry to manage the data from CAD/CAE/CAM software. Systems integrators and product data managers are essential members of ship design teams. With the popularity of digital twins and virtual prototypes, these frameworks may potentially expand to robust information architectures that involve enterprise solutions and real-time data as shown in Figure 41.

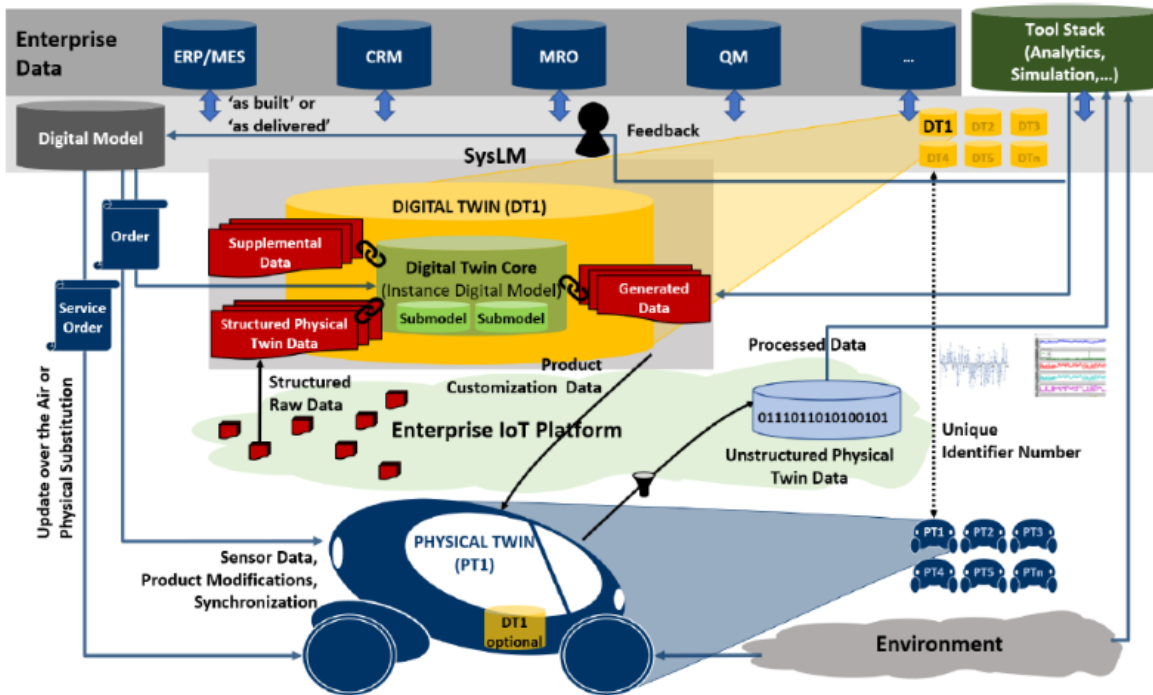


Figure 41 - Sample Framework for Manufacturing [54]

A similar or equivalent idea to 'ship digital twin' has been envisioned since the 1970s in the form of a 'Ship Product Definition Model.' According to [53], 'an important aspect of product definition involves their three-dimensionality. Traditional ship design is carried out in 2D in preliminary stages and extended to 3D in detailed stages. The extension from 2D to 3D results in a large expenditure in time and labor...a product model enables designers to use the same model of a ship from the earliest stages of the design to production.' Figure 42 shows future features and capabilities of a ship product definition.

Naval architects today can have a tool with these functionalities. From years of trying to integrate ship data, our major learnings and setbacks are significant. We now have capabilities such as quicker 2D / 3D design processes, reliable documentation of the whole ship design process, the ability to process and explore several configurations during the early stages, exporting and data exchange capabilities between formats, connection between design (drawing) and performance (analysis), revision control capabilities, precise determination of modeling effects into hydrostatic and hydrodynamics of the design, and parametrization and optimization of geometry and performance (via scripting languages).



**TABLE 13.1V** Full List of Future Requirements for Product Model Program

|   |  |  |
|---|--|--|
| <p><b>Design: Conceptual/Preliminary Design</b></p>   | <p><b>Production: Joining and Assembly Processes</b></p>   | <p><b>Operations Management: Production Engineering</b></p>  |
| <ol style="list-style-type: none"> <li>1. Concept/Preliminary Design Engineering Analysis Tools</li> <li>2. Reusable Product Model</li> <li>3. Develop Initial Build Strategy, Cost and Schedule Estimates</li> <li>4. Classification/Regulatory Body and Owner Compliance Support</li> </ol>   | <ol style="list-style-type: none"> <li>26. NC Programs for Joining and Assembly</li> <li>27. Automated Subassembly/Assembly Processes</li> <li>28. Programmable Welding Stations and Robotic Welding Machines</li> <li>29. Locations Marking for Welded Attachments</li> <li>30. Definition of Fit-Up Tolerances</li> <li>31. Control of Welding to Minimize Shrinkage and Distortion</li> <li>32. Programming for Automated Processes</li> <li>33. Definition of Fit-Up Tolerances for Block Assembly Joints</li> </ol> | <ol style="list-style-type: none"> <li>46. Development of Production Packages</li> <li>47. Development of Unit Handling Documentation</li> <li>48. Parts Nesting</li> <li>49. Development and Issue of Work Orders and Shop Information</li> </ol>   |
| <p><b>Design: Functional Design</b></p> <ol style="list-style-type: none"> <li>5. Connectivity Among Objects</li> <li>6. Tools to Develop Standard Parts, Endcuts, Cutouts and Connections</li> </ol>   |  | <p><b>Operations Management: Purchasing/Procurement</b></p> <ol style="list-style-type: none"> <li>50. Material Management</li> </ol>  |
| <p><b>Design: Detailed Design</b></p> <ol style="list-style-type: none"> <li>7. Automated Documentation</li> <li>8. Detail Design Engineering Analysis Tools</li> <li>9. Design for Fabrication, Assembly and Erection</li> <li>10. Linkage to Fabrication Assembly and Erection</li> <li>11. Automatic Part Numbering</li> <li>12. Interference Checking</li> <li>13. Linkage to Bill of Material and Procurement</li> <li>14. Weld Design Capability</li> <li>15. Coating Specification Development</li> <li>16. Definition of Interim Products</li> <li>17. Consideration of Dimensional Tolerances</li> <li>18. Context-Sensitive Data Representations</li> </ol> | <p><b>Production: Material Control</b></p> <ol style="list-style-type: none"> <li>34. Capabilities for Material Pick Lists, Marshalling, Kitting and Tracking</li> <li>35. Tracking of Piece/Parts Through Fabrication and Assembly</li> <li>36. Communication of Staging and Palletizing Requirements to Suppliers</li> <li>37. Documentation of Assembly and Subassembly Movement</li> <li>38. Handling and Staging of In-Process and Completed Parts</li> </ol>   | <p><b>Operations Management: Shop Floor Resource Planning and Scheduling</b></p> <ol style="list-style-type: none"> <li>51. Provision of Planning and Scheduling Information to Shops</li> <li>52. Work Order/Work Station Tracking and Control</li> <li>53. Detailed Capacity Planning for Shops and Areas</li> <li>54. Collect and Calculate Costs for a Major Assembly</li> </ol>   |
| <p><b>Production: Fabrication Processes</b></p> <ol style="list-style-type: none"> <li>19. Processes to Cut/Form Structural Plates and Shapes</li> <li>20. Documentation of Production Processes</li> <li>21. Information Links to Production Work Centers</li> <li>22. Piece and Part Labeling</li> <li>23. Creation of Path or Process Programs for NC Machines and Robots</li> <li>24. Development of Interim Product Fabrication Instructions</li> <li>25. Simulation of Fabrication Sequences</li> </ol>   | <p><b>Production: Testing and Inspection Guidelines</b></p> <ol style="list-style-type: none"> <li>39. Testing and Inspection Guidelines</li> </ol>  | <p><b>Umbrella: Umbrella</b></p> <ol style="list-style-type: none"> <li>55. Datacentric Architecture</li> <li>56. Computer-Automated as Well as Computer-Aided</li> <li>57. Interoperability of Software</li> <li>58. Open Software Architecture</li> <li>59. Accessible Database Architecture</li> <li>60. Remote Networking Capability</li> <li>61. Full Data Access (Read Only) to All Project Participants</li> <li>62. Assignment of Data Ownership</li> <li>63. User-Friendliness</li> <li>64. Enterprise Product Model</li> <li>65. Integration With Simulation</li> <li>66. Information Management</li> <li>67. Scalability</li> <li>68. Transportability</li> <li>69. Configuration Management</li> <li>70. Compliance With Data Exchange Standards.</li> </ol> |
|   | <p><b>Operations Management: High-Level Resource Planning and Scheduling</b></p> <ol style="list-style-type: none"> <li>40. High Level Development of Build Strategy</li> <li>41. Order Generation and Tracking</li> <li>42. Performance Measurement</li> <li>43. Production Status Tracking and Feedback</li> <li>44. Inventory Control</li> <li>45. High Level Planning and Scheduling</li> </ol>  |  |

*Figure 42 – Future Requirements for Product Model Program in Earlier 2000s [53]*

Computational tools for ship design and shipbuilding are required such as the use of computer algorithms, simulations, and data analysis to support and enhance engineering processes. The main features of computational tools for ship design and shipbuilding industry can be categorized into two main types: features related to business and features related to usability. Features related to business include operations-oriented – Ability to improve operations and processes, cost and efficiency – Ability to reduce costs and enable on-time delivery, and innovation enabling – Ability to enable new and emergent designs and processes. Features related to usability include 2D / 3D models – flexibility to reorient 2D/3D representations, level of detailing – flexibility to provide various degrees of detail, analysis and simulation – coupling capabilities with other analysis and simulation functionalities, integration Capabilities – ease of connection or integration with other tools, formats, and Information, and data handling – ease of Information management from storage, access, analysis, transformation, and sharing.

For usability features, it is important to consider how the tools enable integrated and or fragmented design practices. Integrated design practices have features with single source, tools are able to perform multiple tasks, encapsulated data/info, database Integrated, exchanging freedom for coherence, and loss of opportunity (bounded options). These usability features are not one-

dimensional, and trade-offs need to be selected. These trade-off decisions will also vary based on the lifecycle phase as shown in Figure 43.

|                          | 2D/3D  | Level of Detailing   | Analysis and Simulation   | Integration Capabilities  | Data and Handling   |
|--------------------------|--|--|---|---|---|
| 2D/3D                    | 2D/3D  | Comprehensive models with capacity to filter and extract multiple view points  | Model and analysis tools coupled together, with simulation on the go, promising possibility to optimize topology/arrangement              | All in one software, either able to provide most of the analysis, either able to incorporate older compatible models in to the larger system          | One file with multiple models, larger size  |
| Level of Detailing       | Every level of detailing requires a new model                                | Level of Detailing   | Simulation of the whole model, with filter in specific parts and analysis of overall consequences. Time consuming and complex to analyse. | Flow of detailing, with zooming and filtering, with categories division such as taxonomy, size, ownership, spatial position, functional requirements. | Few files with large data (size), and zoom/filtering capabilities inside the software to delimit boundary at any stage.             |
| Analysis and Simulation  | A new model for every new analysis, with minimal info required in each model | One simulation of one small part or portion of the whole, a new simulation for each time/ phase/ degree of hierarchy. Faster and simpler | Analysis and Simulation   | "All in one" software, such as FEM, CFD, dynamics, thermodynamics sharing the same set of inputs.   | Inputs and outputs shared among simulation. A single (or fewer) large data sets with multiple values and attributes to be filtered. |
| Integration Capabilities | Single software for one task, one model for each task                        | Every level of detail has very defined borders, not connected in a flow (one file for each level)  | One simulation/ software for one type of behaviour, no connection with other simulations. Separated and individual inputs and outputs.    | Integration Capabilities  | Single or fewer files with simulation and results integrated. Better on see multi-domain consequences, harder to filter.            |
| Data Handling            | Individual files for each model, small size, large number of files           | Separated data for every level, with defined amount of required data/ files to establish a level   | Very defined boundary of inputs and outputs. Every simulation has it's own data.  | Separated files, with separated analysis and results. Easy to filter, hard to see multi-domain consequences.  | Data Handling   |

Figure 43 – Trade-off Decisions for Lifecycle Phases [55]

These practices reflect and further facilitate either decentralized, centralized, or distributed information systems. Decentralized information systems perpetuate information silos that do not correspond with each other. There are pros and cons to the different information systems. For instance, centralization of data allows for easier decision-making and data retrieval. Whereas with decentralization, the risk of single points of failure is decreased. The trade-offs between centralization and decentralization are illustrated in Figure 44.

With the current status quo of how ship design and shipbuilding activities are performed, what degree of integration would be feasible throughout the entire lifecycle? Currently, ship design companies use a combination of various business enterprise solutions to manage these integration needs and enable better planning and resource management. These enterprise tools include Enterprise Resource Planning (ERP) and Product Data Management (PDM). A common ship design data management solution today includes multiple databases and servers to manage technical and planning data. However, these solutions still face common concerns in maintenance and usability, including the lack of automatic information flow processes. These concerns are echoed by the technical and administrative staff in SD&SB firms. In Ulstein, for example, the persistence of information silos and difficulties in information exchange leads to inefficiencies in data retrieval as shown in Figure 45.

| Parameter                       | Centralized   | Decentralized  |
|---------------------------------|---|--|
| <b>Control</b>                  | Users lose ownership of their data as assets are transferred to central servers.  | Users retain ownership of their data.  |
| <b>Third-Party Intermediary</b> | A centralized exchange serves as a go-between for the buyer and the vendor. Due to the engagement of third parties, it charges operations fees. | Decentralized exchange serves as a “trustless” platform for transaction authorisation. Transactions are free of middleman fees.                              |
| <b>Single Point of Failure</b>  | A single point of failure in a centralized network can jeopardise the entire network's security.  | Because the information is disseminated throughout numerous blocks that are added together, a decentralized network does not have a single point of failure. |
| <b>User-Friendly</b>            | Beginners will find it simple and intuitive to operate.   | Complex, will require education/training.  |
| <b>Anonymous</b>                | Centralized networks cannot keep user data anonymous.   | Decentralized networks are built on the principle of anonymity.  |

Figure 44 – Trade-off Between Centralization and Decentralization of the Different Information Systems [56]

## THE VOICE OF ULSTEIN



Figure 45 – The Voice of Ulstein (Internal data of SEUS from Ulstein)

### 2.6. Distinctions of the Shipbuilding Process

What solutions would enable better integration of the data across different lifecycle phases as well as vertical coordination of different stakeholders? The digital twin trajectory was originally designed to complement Project Lifecycle Management (PLM). Initially, the digital twin concept was developed to model how physical and virtual systems should interface, naturally leading to the development of tools

for the management of product data. Today, PLMs help companies to capture, codify, process, and communicate product knowledge across their organizations. Parallel models exist in other industries. Building Model Information (BIM) in construction has the long-term intent of capturing building data and processes in an integrated and interoperable manner. The potential of PLM and future hopes cover not only product data, but also database management, modeling tools, and process management.

PLM methods provide a way of dealing with huge amounts of data in a complex product's life cycle. Many techniques, such as efficient information indexing, database management, product decomposition and analysis, and project management. A PLM tool can be coupled with other enterprise solutions such as ERP/PDM and other CAD/CAE/CAM software as shown in Figure 46, Figure 47, and Figure 48.

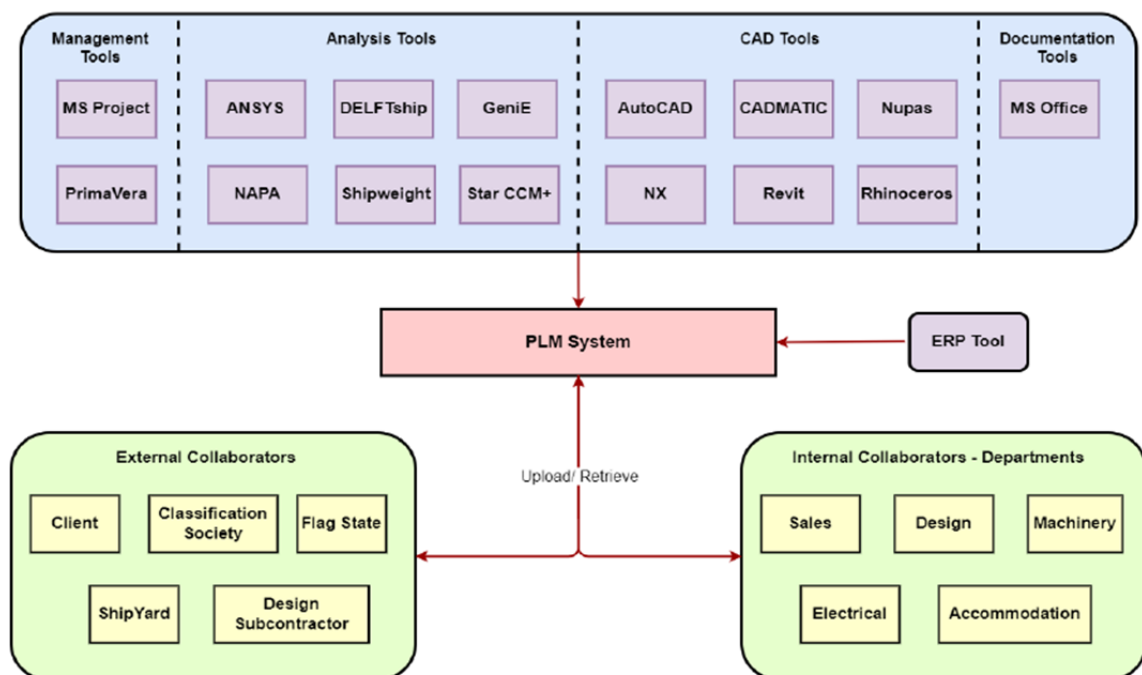


Figure 46 – PLM Framework [26]

In current practice, physical taxonomies are most widely used in ship design. However, as Pal suggests, there are limitations in the use of these physical breakdowns as ideally, the information model for defining the ship should also be associated with the resource data during production [24]. The resource data includes not only information on the Product, Process, Resource, and Production schedule but also 2D drawings, documents, production method, and the attributes of each component [24]. Moreover, owing to the complexity of a sub-system [57], the dependencies among tasks, and the many subjective and non-quantitative factors in the process of WBS execution ([58], [59]) may not be captured and a large amount of rework will occur leading to project delay, resource waste, cost increase, and many other problems, hindering development [60].

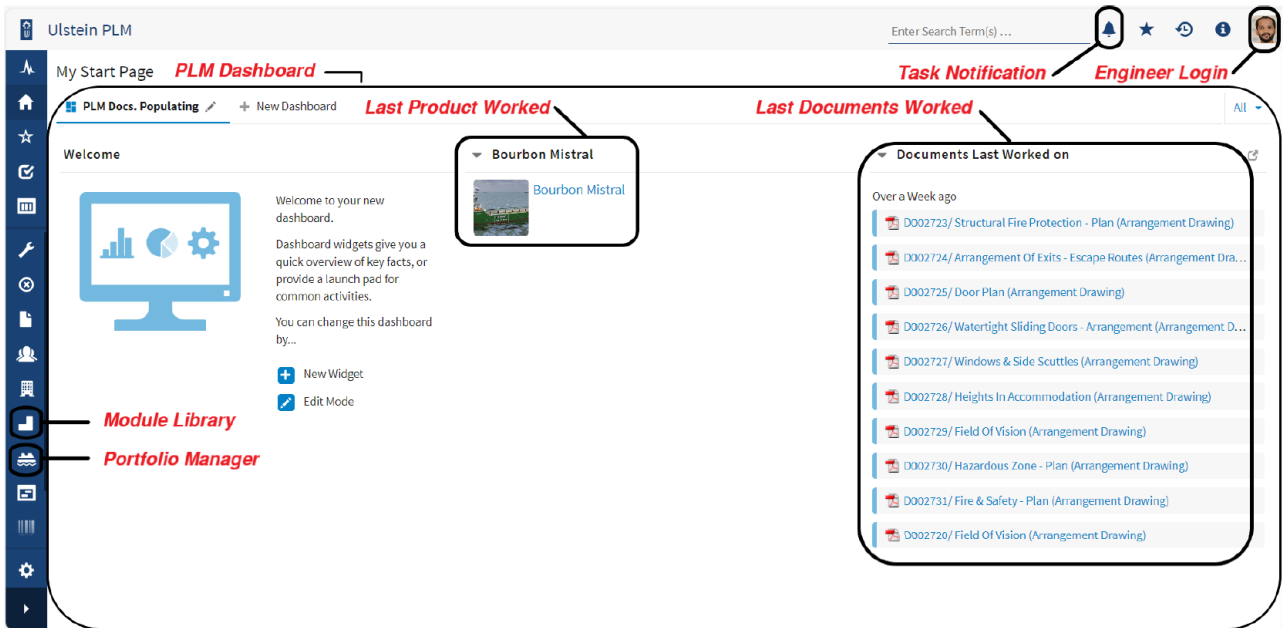


Figure 47 - PLM Framework [26]

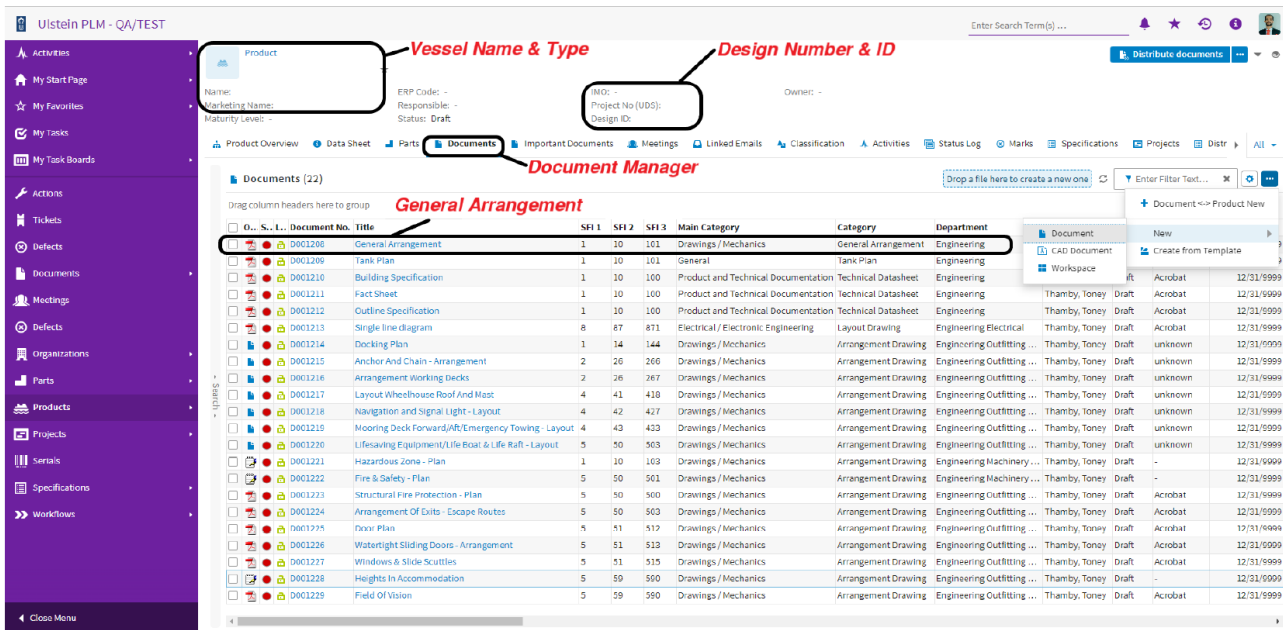


Figure 48 - PLM Framework [26]

There are currently no standardized solutions that integrate all these taxonomies to make ship design and planning more efficient. Due to path dependence, it is also more appealing to remain in the status quo as evidenced by ship designers' lack of motivation to use novel solutions or software. The complication that may arise from integrating with existing software tools also adds to the resistance to exploring new solutions.

Pal highlights that introducing a centralized and adaptable data structure is one way to resolve the complications arising from rigid hierarchical WBS [24]. Pal suggests that these rigid data structures

lead to excessive and unnecessary conversion and missed opportunities in data maximization and attribute retrieval. Additionally, these WBS do not easily integrate with the shipyard's BOM (Bill of Materials) and BOP (Bill of Processes). He proposed the use of the 4DG Framework from Siemens PLM Teamcenter which provides users a structure-agnostic approach to defining basic units of ship data that can be flexibly 'partitioned'. This approach was evaluated by Gaspar and Levišauskaitė [61]. Although they show the potential of this framework, it is unclear whether this would be most effective in yards as it still lacks temporal attributes needed for planning. 4DG is also based on *component-based software engineering* where there is a tendency towards the separation of concerns among various parts of a software system. This type of solution deviates from agile practices that are most effective when certain information is unavailable.

Other papers and studies have attempted to use a more advanced PWBS approach by combining PWBS with a Gantt Chart and they found up to 86% reduction in man-hours. Rahman et al. argued that these studies show that a PWBS method that integrates information from HBCM (Hull Block Construction Method), ZOFM (Zone Outfitting Methods), and ZPTM (Zone Painting Methods) is a satisfactory solution and that applies to different shipyards, regardless of their varied scheduling approaches [41]. Apart from the use of advanced PWBS tools, alternative solutions have also been proposed in the form of implementing a PODAC or Product Oriented Design and Construction Cost Model recommended by Koenig and Christensen [41] and the use of a CIM system or Computer Integrated Manufacturing philosophy where the aim is to integrate all planning data and costing into CAD [62].

As shown in Figure 26, each strategy faces its own risk, both in data and systems integration, due to the variability in the stakeholders, interactions, and information exchange. Every yard will have unique facets of its design and production. In this section, examples of a process map for the shipbuilding process will be presented. Strategies are for shipbuilding processes, comparing different stages from contract initiation to final delivery. The strategies are designed to optimize various aspects of production, particularly focusing on the assembly and outfitting processes. Strategies have 8 stages: Conceptualization, product engineering, concurrent steel block & parts fabrication, assembly, ship erection, dock outfitting, quay outfitting, and commissioning & testing.

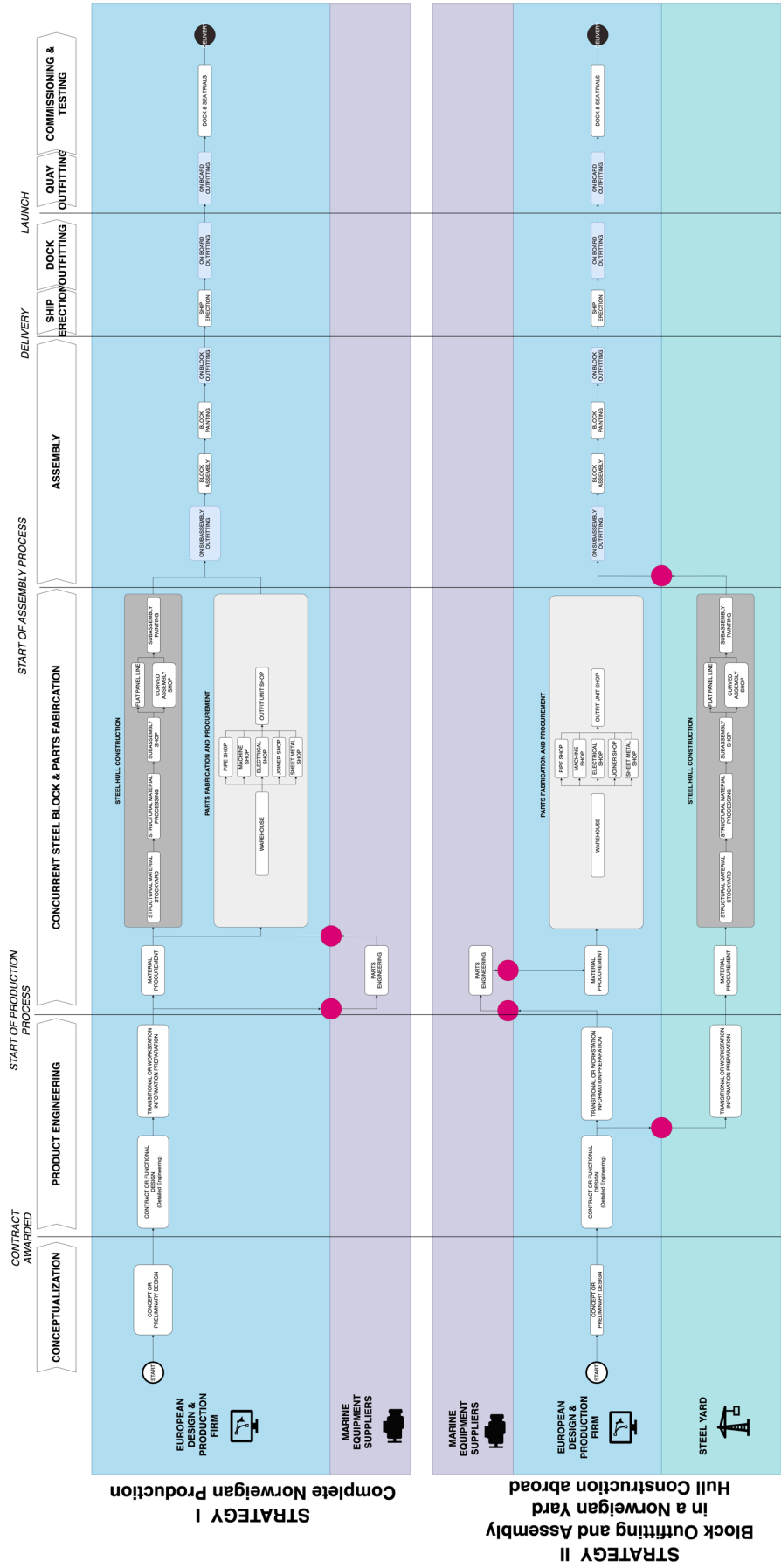


Figure 49 - Process Map of Strategy I & II (Internal data of SEUS)

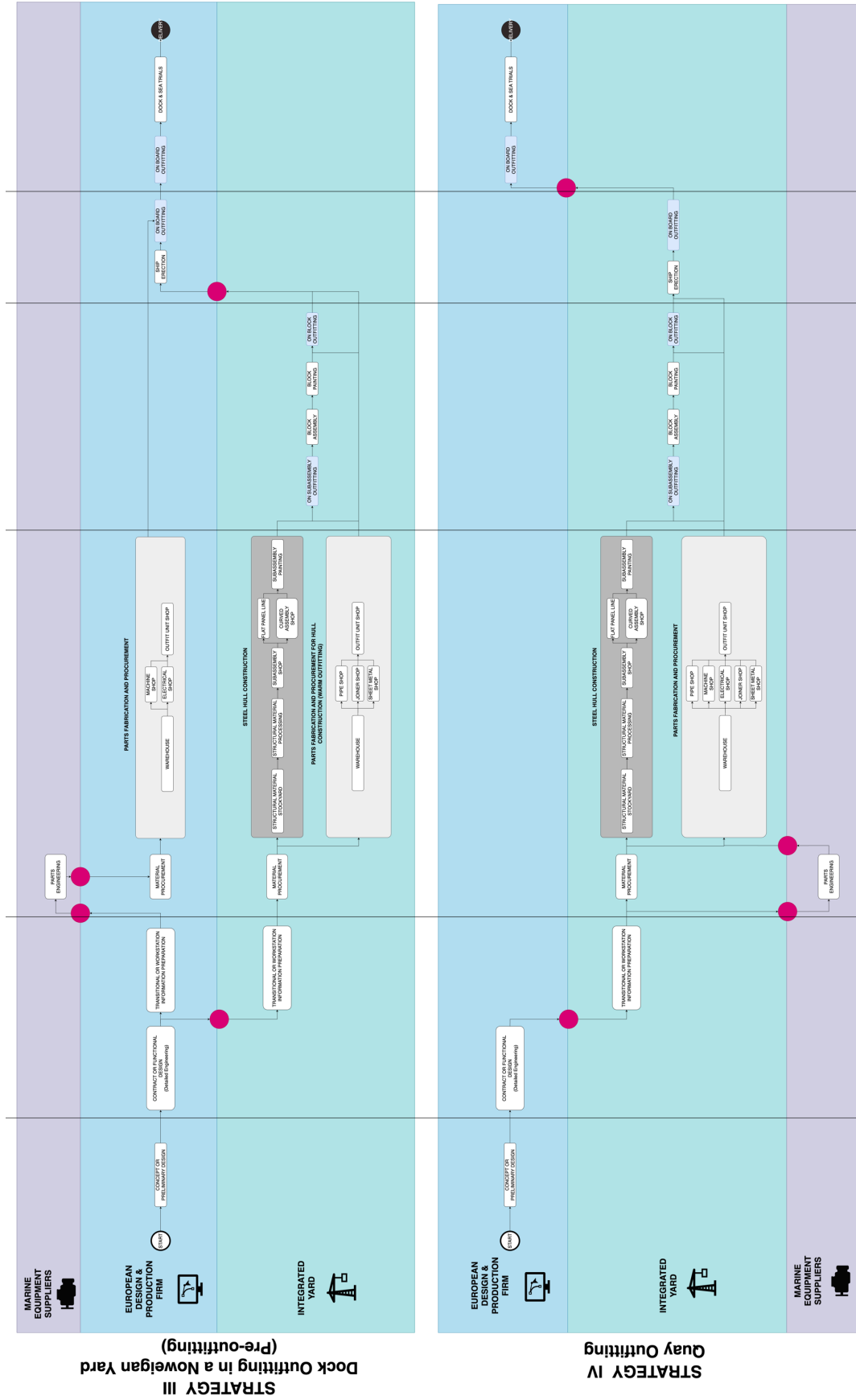


Figure 50 - Process Map of Strategy III & IV (Internal data of SEUS)

## 2.7. Single Source of Truth Concept or Attempt

We reviewed the proposed methods and tentatively concluded that a new Digital SSoT solution, including PLM, is required. Other solutions have alternatively been proposed in the form of improved data architecture and management. The digital twin also could be a solution that would enable better integration of the data across different lifecycle phases as well as vertical coordination of different stakeholders. The digital twin trajectory was originally designed to complement Project Lifecycle Management (PLM). Initially, the digital twin concept was developed to model how physical and virtual systems should interface, naturally leading to the development of tools for the management of product data. Today, PLMs help companies to capture, codify, process, and communicate product knowledge across their organizations. Parallel models exist in other industries. Building Model Information (BIM) in construction has the long-term intent of capturing building data and processes in an integrated and interoperable manner. The potential of PLM and future hopes cover not only product data, but also database management, modeling tools, and process management [63].

For example, PLM solutions to manage the lifecycle documentation of the vessel have been explored by Andrade et al [64]. Commercial product lifecycle management (PLM) software is gaining more and more attention (and clients) in the ship design industry, with the promise of presenting a common standard to create, provide storage, and share capabilities of the value-chain data across the ship design community. PLM can be defined as the activity of managing a company product across its life cycles in the most effective way [65] and it is one of the best-known methods to maintain a good organization of the product's different parts, services, costs, and suppliers through all the cycles involving a product life, from conception to scrapping. The PLM umbrella embraces many other concepts, such as modularization tools, product and systems architecture, libraries, product data management, and enterprise content management [64]. A PLM tool can be coupled with other enterprise solutions such as ERP/PDM and other CAD/CAE/CAM software. Several academic attempts have been made focused on theoretically defining a PLM-centric approach for Shipbuilding.

However, there are several concerns with the application and adoption of PLM:

- Additional work to add existing data in the new format/standard/library
- Lack of ship design terms, tools, and methodologies incorporated in the available tools, with the designer adapting to a more mechanical engineering approach to traditional ship design analyses.
- Lack of seamless integration with third-party ship design tools
- Proprietary and closed software package, constraining customization
- High cost to acquire, install, train personnel, and keep servers running.
- Resistance to experienced engineers to use a new tool
- Risk of being locked to a system, and losing independence if features and license terms change
- Ignore that individuals have different preferences on how they solve the problem and that a certain methodology proposed by the PLM system is not the most effective among users
- Inability to incorporate commonly used ship design files (data types) in the database, as well as to open the large diversity of CAD files

- Forget that Word, Excel, and PPT are key means to compile and share information, forcing internal reports

Outside information-related solutions, other literature aims to shed light on managerial solutions to better handle the planning and scheduling of ship design and production. One of which is the use of Lean Project Planning as described by Emblemvåg for Vard, which seeks to eliminate gaps in work execution preconditions among others [1]. Work done by Okubo suggests that there are ways managerial decision-making can also be made more strategic with the use of simulation-based scheduling [46].

Overall, these studies provide insight into the importance of combining information technology, particularly one designed for horizontal integration such as PLM, and social collaboration to continually make the ship design and shipbuilding process as efficient as possible.

Perceptions of PLM usage vary per person in SD&SB firms. For example, in Ulstein, there are positive perceptions of how PLM contributes to better control of ship design data. However, there are concerns with the rigid documentation required. In the path towards digital transformation, it is common to face a trough of disillusionment. There are proposed ways the industry can de-risk the exploration of new solutions or better define expectations, and the ways to arrive at an optimistic future for ship design and shipbuilding are as follows:

- Re-use and build up on former designs, allowing the designer to fetch former designs from a database, building up new concepts based on the new information
- Re-using advanced 3D models for many value-chain phases (sales, concept, basic, construction).
- Keep the collected and analysed data as accessible as possible during the design process
- Access to the analyses made during the design process, options, and behavior of the systems under the multiple operational scenarios studied, without the filter of a locked proprietary system.
- Must integrate smartly the data used as input and gotten as output from the available ship design tools, as well as incorporating empirical knowledge from stakeholders.

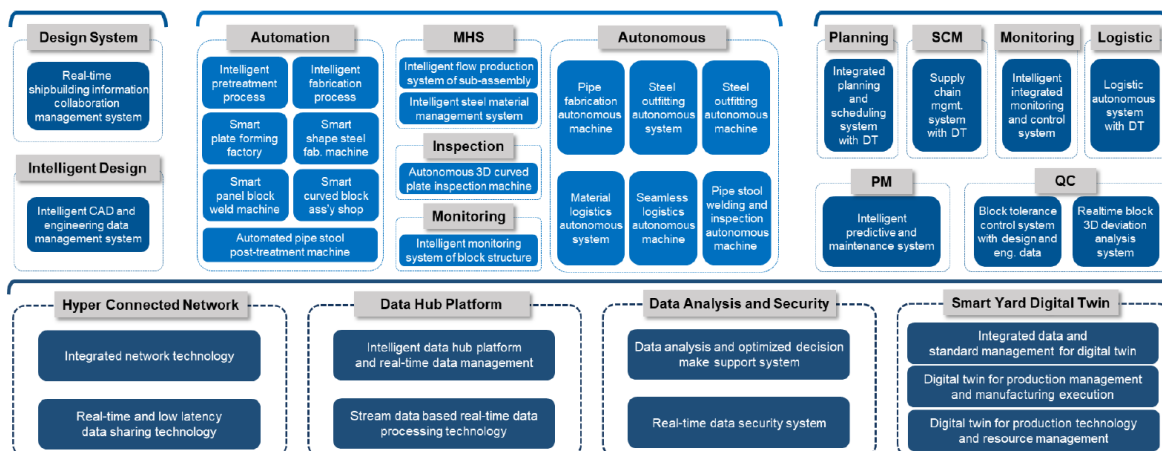


Figure 51 - Digital Shipyard Maturity Levels [66]



As part of the SSoT, certain desired elements are considered covering expertise in ship design and shipbuilding, CAD/CAE/CAM functionalities, and information management as shown in Figure 52. And Figure 53 and Figure 54 show examples of linking, visualization, and sharing design, production, and operational ship information.

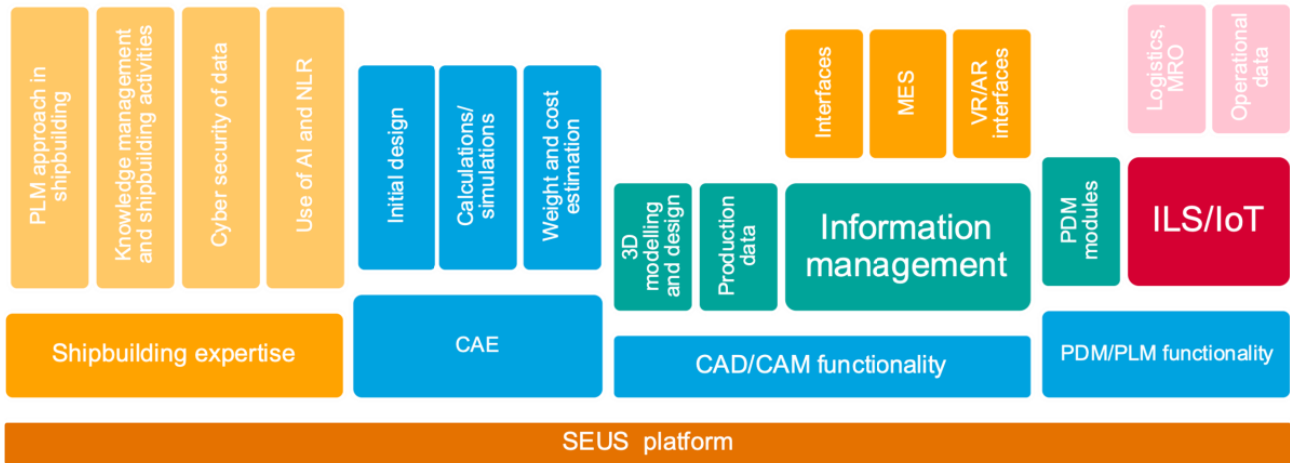


Figure 52 – SEUS Smart Platform Desired Elements [98]

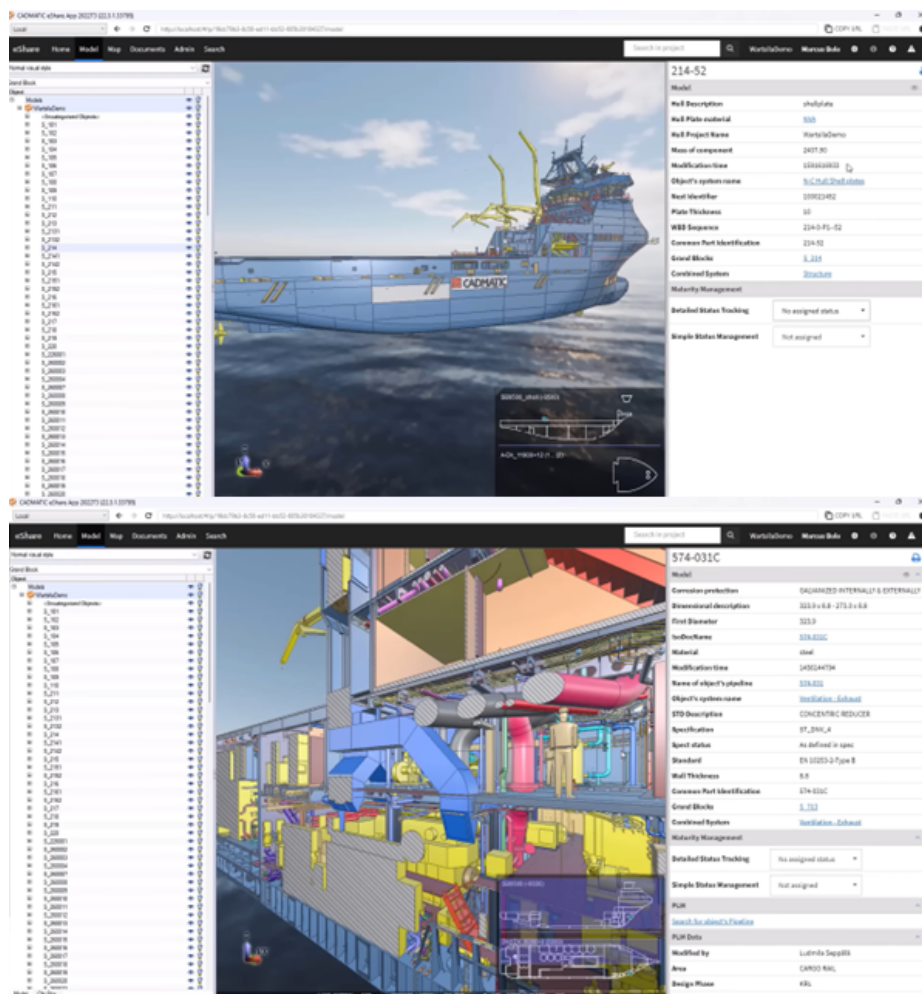


Figure 53 – CADMATIC's eShare for Linking, Visualization, and Sharing Design, Production, and Operational Ship Information (1) [97]

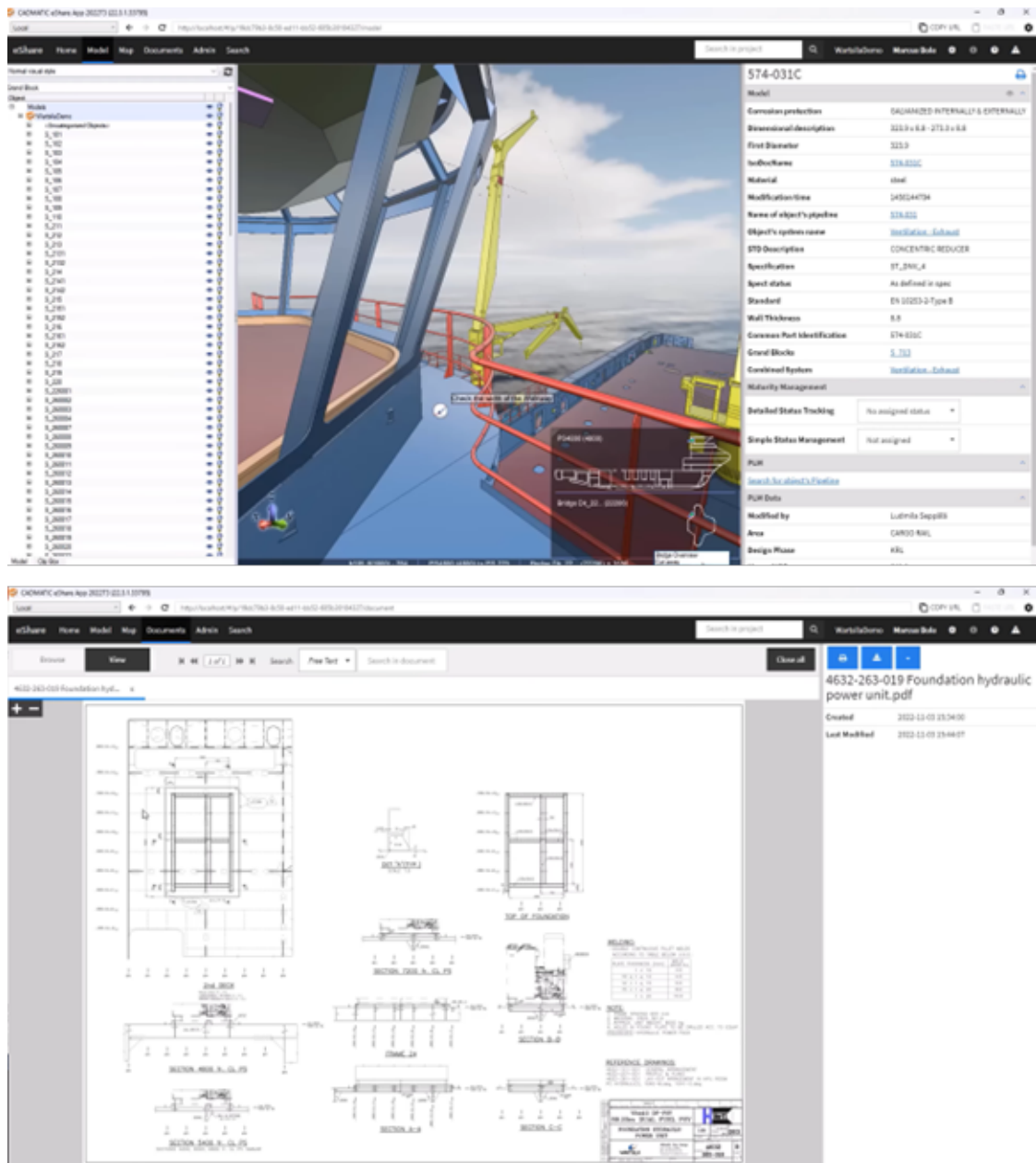


Figure 54 - CADMATIC's eShare for Linking, Visualization, and Sharing Design, Production, and Operational Ship Information (2) [97]

## 3. References of Best Practices in European Ship Design and Shipbuilding

To collect and organize the references for this report, we employed a systematic and comprehensive approach. Initially, we conducted a thorough literature review using academic databases, industry reports, and authoritative sources to identify relevant studies, articles, and publications related to European shipbuilding and ship design. We prioritized sources that offered substantial insights into the best practices, methodologies, and technological advancements within the European maritime industry. We categorized the references based on the chapters and sections of the report to ensure they align with the content's structure.

We supplemented our research with 'Comprehensive Best Practices Research in European Ship Design and Shipbuilding' to include comprehensive best practices research. This research includes more figures, graphs, and material that can be presented in a slide deck format. The research is supplemented in Appendix A, which includes more references for best practices. This report and the references in the slide deck from Appendix A share the same numbering.

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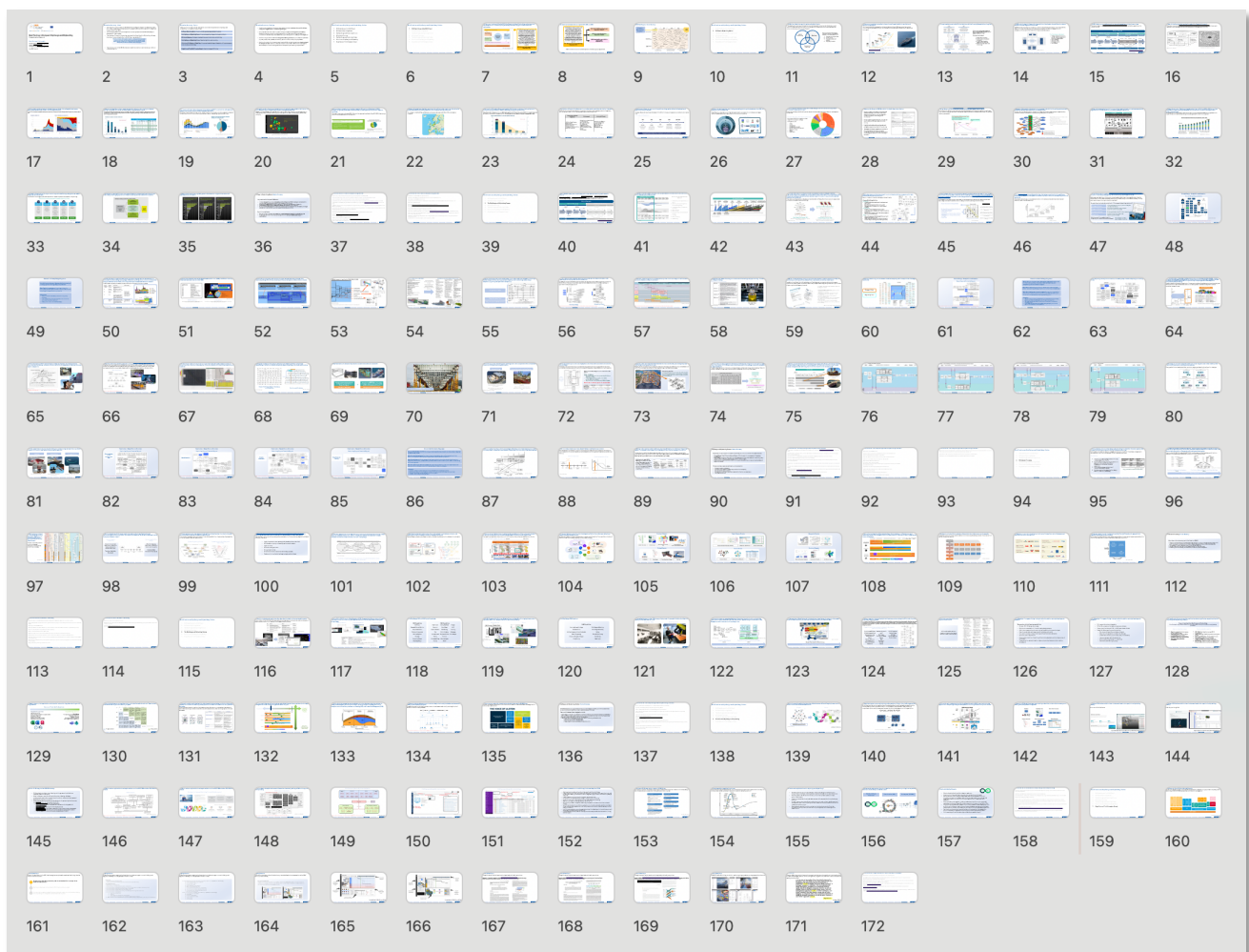
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# Appendix A – Comprehensive Best Practices Research in European Ship Design and Shipbuilding

This compilation is connected to ‘Results and Analysis of the Best Practices Research’. The objective of this research is to provide an overview of the State of the Art of Shipbuilding in Europe and to provide descriptive summaries, user stories, and other research material (articles, synopsis for white papers, abstracts of research, etc.) in a what that can be used further for software development input and as a coordination canvas of the SEUS project.

This deck contains 172 slides, and can be found at the SEUS repository (<http://seus-project.eu/>)





**SEUS**  
Smart European  
Shipbuilding



# Best Practices in European Ship Design and Shipbuilding

## Comprehensive Research

### Work Package 1 Deliverable

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June 2024, Version 3

## Executive Summary - Intent

- This compilation is connected to the SEUS Best Practices Baseline (Milestone 2, M12), Deliverable D1.1 – Results and analysis of the best practices research (M18), and Deliverable D1.2 – Result and analysis of the survey (M18).
- This version is updated in size and scope from the version presented at the SEUS Workshop on November 15<sup>th</sup> (Netherlands)
- The objective of this work is to provide an overview of the State of the Art of Shipbuilding in Europe, focusing on the aspects tackled by the SEUS Project, as stated in D1.1:

*“Results and analysis of best practices research (...) will be presented as descriptive summaries, user stories, and other research material (articles, synopsis for white papers, abstracts of research, etc.) in a way that can be used further for software development input and as a coordination canvas of the project.”*

- The authors expect that the SEUS partners can use this as a reference and common ground for our understanding so far.

## Executive Summary - Topics

With respect to the intent, this draft explores the current state of digitalization in ship design and shipbuilding, covering the following themes:

**EU Place in Shipbuilding Market** – Current trends in European ship design and shipbuilding industry.

**The Ship Design and Shipbuilding Process** – Current practices and logical stages in the ship upstream lifecycle.

**Multi-domain Taxonomy** – Paradigms in how ship data is represented in ship design and shipbuilding.

**The Ship Design and Shipbuilding Toolbox** – The state of digital tools used in the industry.

**Distinctions in Ship Design and Shipbuilding** – Unique perceptions and challenges to the application of lifecycle management tools in ship design and shipbuilding.

**Single Source of Truth (SSoT) Concept or Attempt** – Attempts to develop an SSoT solution.

## Executive Summary - Findings

- The European shipbuilding industry is unique due to its focus on **custom and specialized ships**, **heavy multi-organization**, and **offshoring strategies**.
- European maritime cluster and ecosystem is well-positioned to **tackle digital transformation**. Better ship data management can enable more effective (1) decision-making and planning, (2) communication between disparate stakeholders, (3) knowledge retention, and (4) risk management.
- An effective digital solution can tackle **integration challenges** that exist across domains (functional, physical, people, time, process, and context), parties involved, and ship lifecycle phases.
- Solutions focused on lifecycle management, such as PLM, can help to promote a **cohesive view of the ship model data**. However, enterprise solutions such as PLM or ERP still face challenges in terms of adoption, time for training, and lack of interoperability with existing third-party tools.

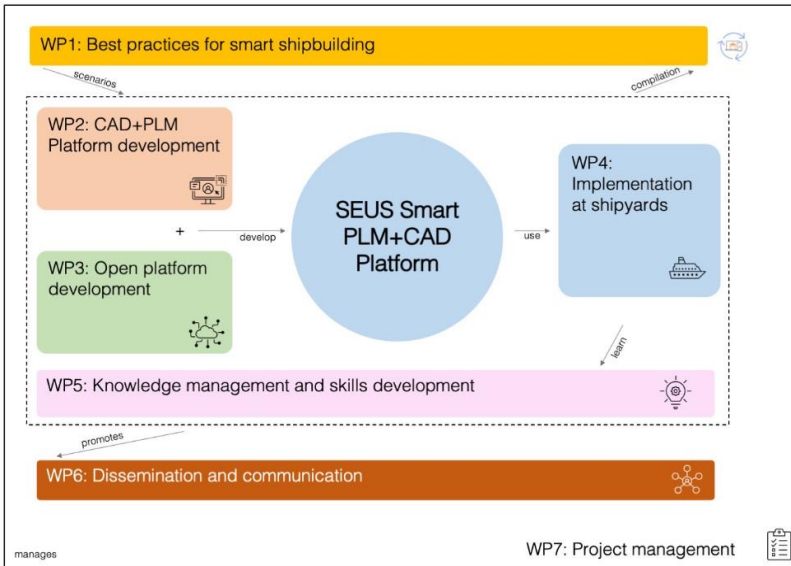
## Best Practices on Ship Design and Shipbuilding: Outline

1. EU Shipbuilding and the SEUS Project
2. EU Place in Shipbuilding Market
3. The Ship Design and Shipbuilding Process
4. Multi-domain Taxonomy
5. The Ship Design and Shipbuilding Toolbox
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## Best Practices on Ship Design and Shipbuilding: Outline

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This document is a live draft for the **WP1: Best Practice for Smart Shipbuilding** and is intended to be a compilation of literature regarding ship design & shipbuilding processes and maritime digitalization.



This WP addresses research, evaluation, and compilation activities to identify the best practices for the smart PLM approach in shipbuilding. It aims to build a new body of knowledge for the value shipbuilding can expect to gain from digitalization, a single-source of truth approach with compelling information and data sharing for all stakeholders. The applied nature of such research and interconnection with the computational tool development process (WP 2,3) and end-user perspectives (WP5) will deliver a practical approach to innovation and implementation of EU shipbuilding industry expertise.

**WP1: Best practices for smart shipbuilding**  
Responsible: NTNU

This draft is also intended to be an input to **WP2, WP3, and WP5**.

This WP addresses research, evaluation, and compilation activities to identify the best practices for the smart PLM approach in shipbuilding. It aims to build a new body of knowledge for the value shipbuilding can expect to gain from digitalization, a single-source of truth approach with compelling information and data sharing for all stakeholders. The applied nature of such research and interconnection with the computational tool development process (WP 2,3) and end-user perspectives (WP5) will deliver a practical approach to innovation and implementation of EU shipbuilding industry expertise.

**WP1: Best practices for smart shipbuilding**  
Responsible: NTNU

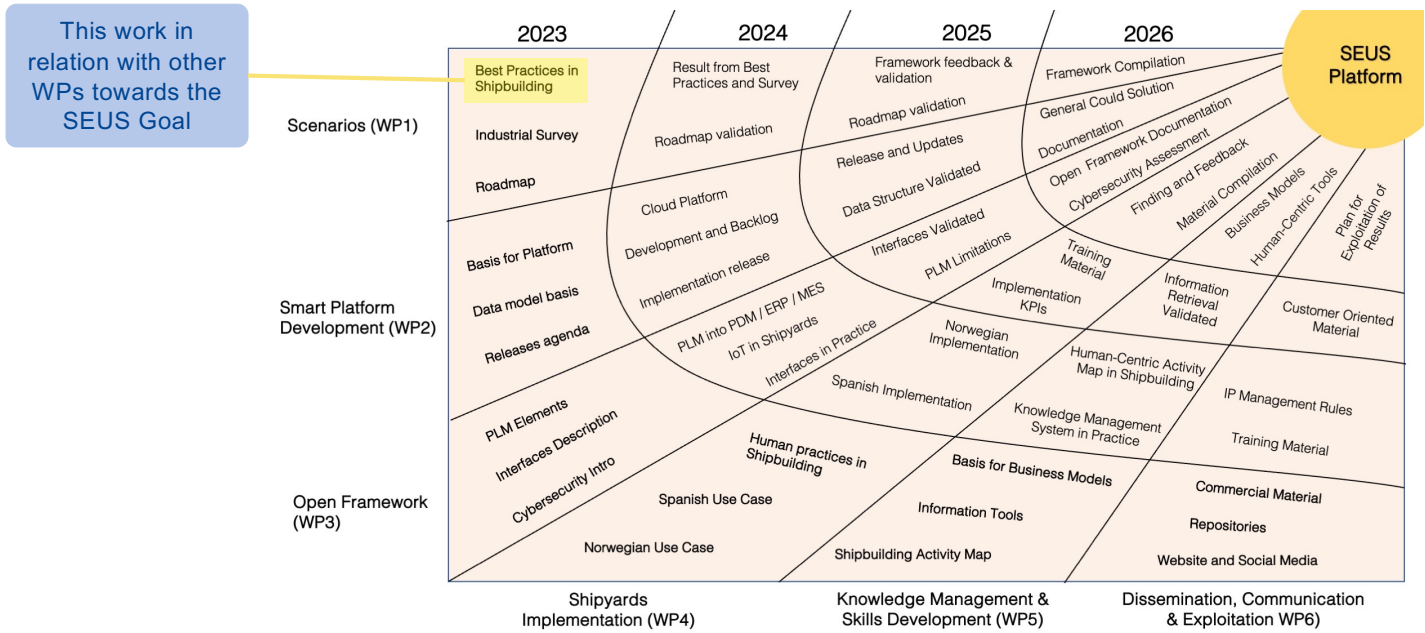
**WP2: CAD + PLM Platform Development**  
Responsible: CADMATIC

**WP3: Open Platform Development**  
Responsible: CONTACT

**WP5: Knowledge Management & Skills Development**  
Responsible: UTU

Additional feedback on sections that require modification is greatly appreciated.

## SEUS Sun Diagram – Visual Roadmap

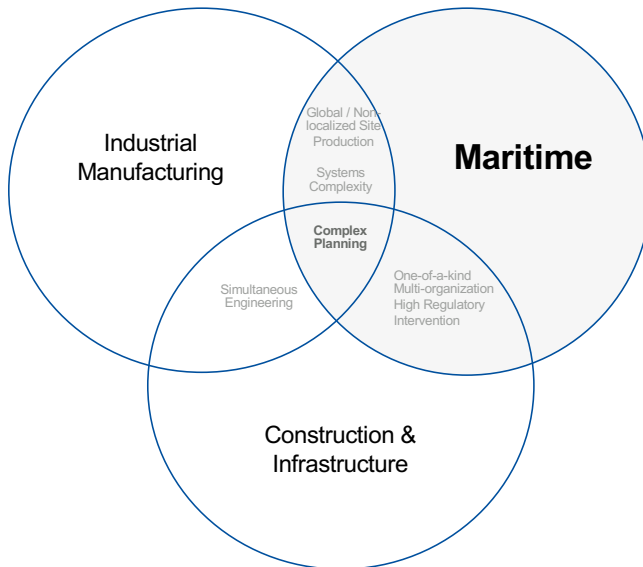


## Best Practices on Ship Design and Shipbuilding: Outline

1. EU Shipbuilding and the SEUS Project
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## The Maritime Industry is a peculiar and one-of-a-kind industry.

The industry takes on unique features from manufacturing and construction. As it falls between craft production (Engineer-to-Order) and continuous production (Assembly-to-order), best practices from either industries are not directly transferrable.

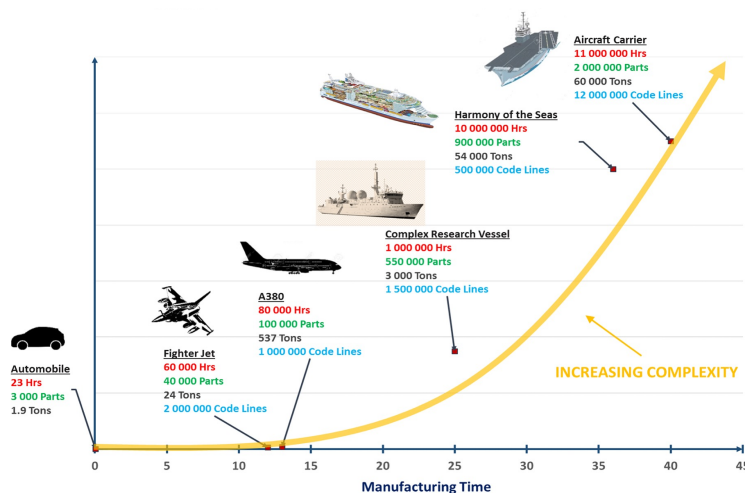


Four peculiarities of the industry, adopted from Emblemvåg (2014) [1]:

1. Temporary multi-organization
2. Site Production
3. One-of-a-kind nature of products
4. Regulatory Invention

## Ships are more complex to manufacture than other craft vessels, both in terms of size and manufacturing difficulty.

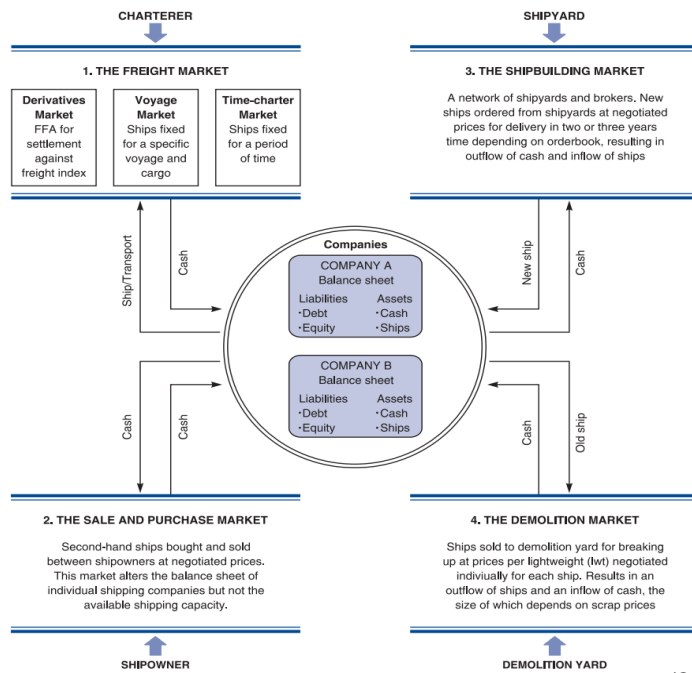
A 537-ton Airbus A380 comprises four million individual parts from 1,500 companies from multiple countries globally (Slutsken, 2018 [2]). On the other hand, a USS NIMITZ Aircraft Carrier has about a billion parts.



USS Nimitz Class  
(Naval-Technology)

<https://www.cesa.eu/the-industry> (Adopted from Cottrell, et al. (2009) [3])

## Four main markets comprise the Maritime Industry and drive the supply/demand of vessels globally.



(Stopford, 2007 [4])

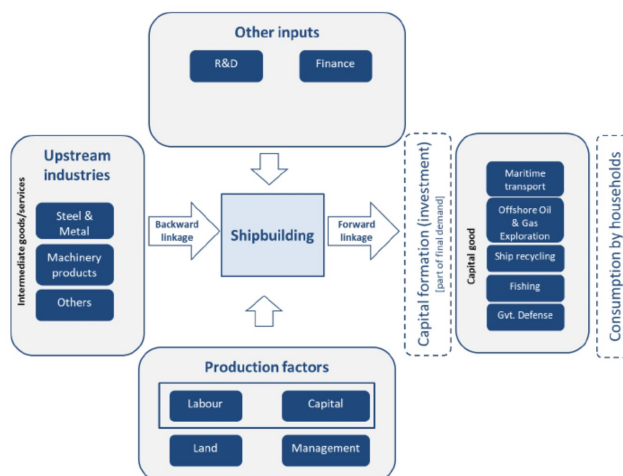
Of these markets, **the ship design and shipbuilding (SD&SB) market** is the most **capital-intensive** to disrupt.

Complications arise due to:

1. High product complexity
2. Lack of product and process information
3. Low-Risk appetite due to regulatory and safety risks
4. Need for external incentives to drive change

## SD&SB market is heavily influenced by these global maritime trends, along with local production factors and a wide-range of clientele needs.

SD&SB clientele may vary from the navies, cruise lines, large shipping and freight companies (COSCO, Maersk, Frontline, etc.), shipping industrial conglomerates (Hyundai, Mitsui, Kawasaki, etc.), oil companies, offshore contractors, and other entrepreneurial shipowners.



(OECD, 2023 [67])

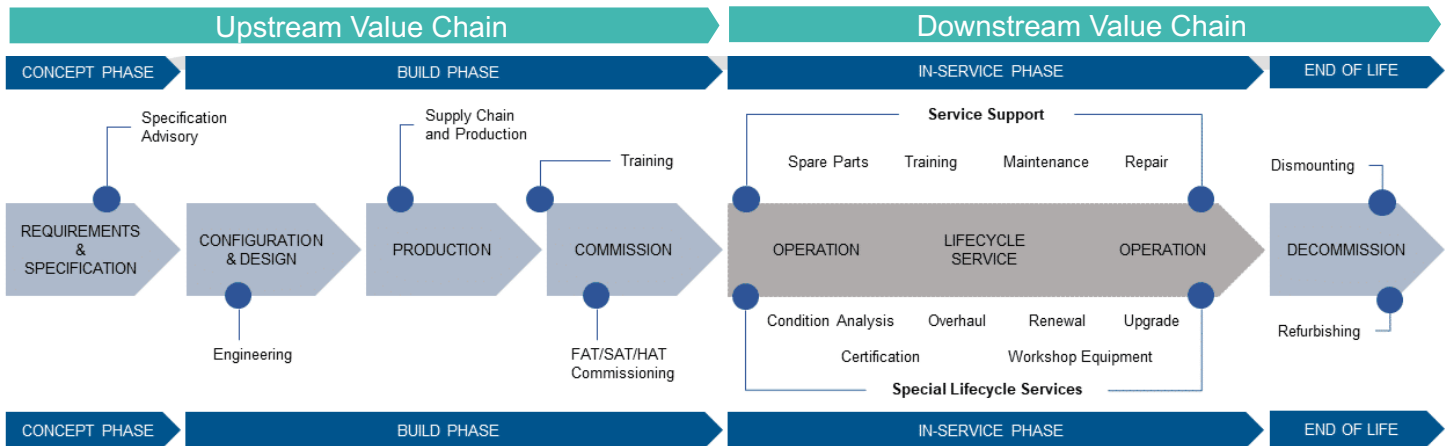
### The 5 main types of products:

- Trading vessels (oil tankers, bulk carriers, containerships are the 3 highest-volume ship types)
- Offshore vessels
- Industrial vessels
- Passenger vessels
- Naval Vessels

**SD&SB Industry covers a wide range of services and companies providing these services.**

Companies support the design, build, operations, and decommissioning of a ship throughout the entire vessel's lifecycle.

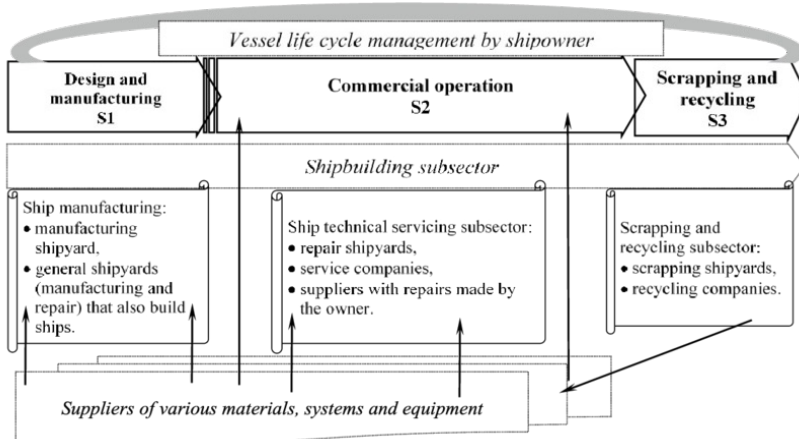
## Ship Lifecycle



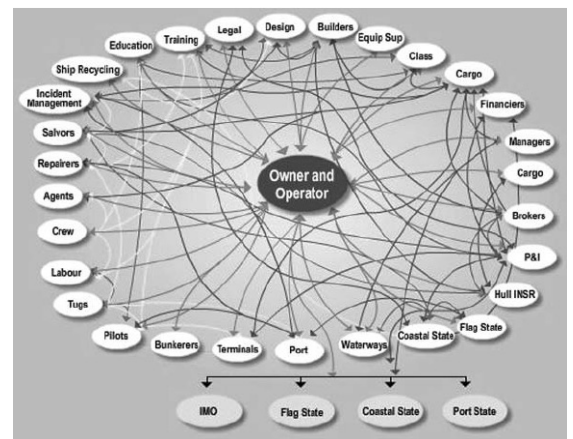
<https://www.gabler-naval.com/lifecycle/> [5]

**These stakeholders are highly coupled throughout the lifecycle of the vessel.**

Companies ranging from design firms, yards, operators, suppliers, and scrapping yard all closely work together from the ship design and manufacturing stages to scrapping and recycling.



(Montwiß, et al., 2018 [6])

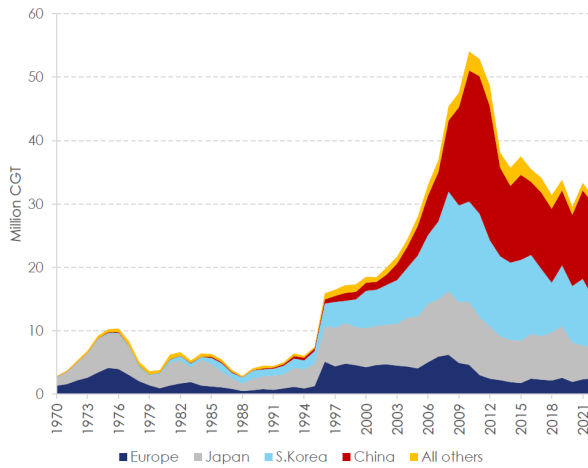


(Lützhöft, Grech & Porathe, 2013 [7])

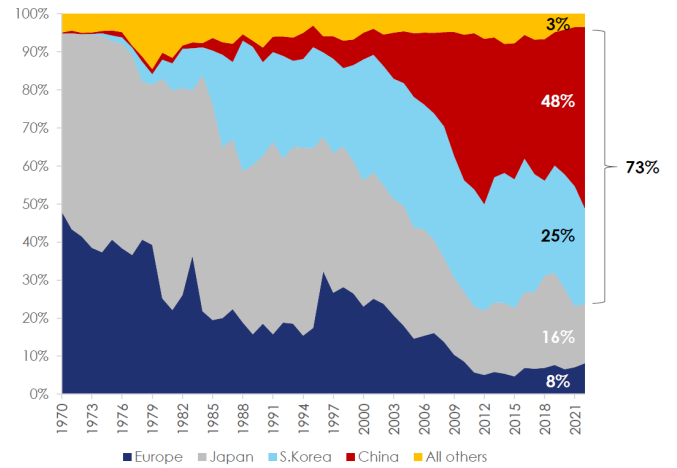
Despite a highly distributed network of stakeholders worldwide, Asian shipyards have become economically attractive due to lower labor and materials costs.

Up to 73% of global newbuild deliveries come from China and South Korea while Europe only shares about 8%.

Deliveries in million CGT



Share of deliveries by country (in %)

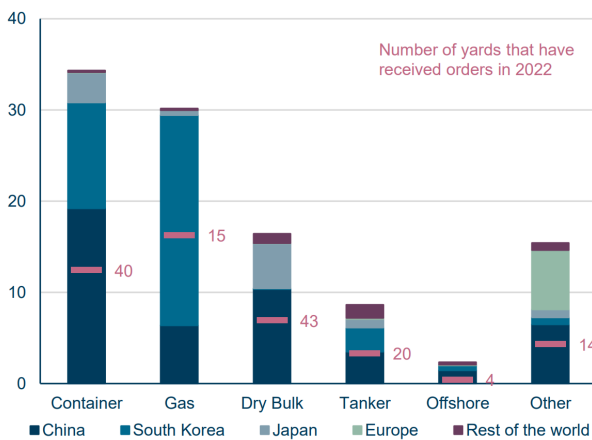


(Clarksons, 2023 [68])

Common ship types like container vessel, gas, dry bulk, and tankers have the highest demand among vessel types. These ships are mainly produced in non-European yards.

Europe dominates the passenger and non-carrying cargo (NCC) vessels market to distinguish itself from competitors. In 2022, Europe comprised around 78% of global passenger vessel deliveries and around 30% of specialized vessels.

Orderbook by segment and region (million cgt)



(Danish Ship Finance, 2023 [13])

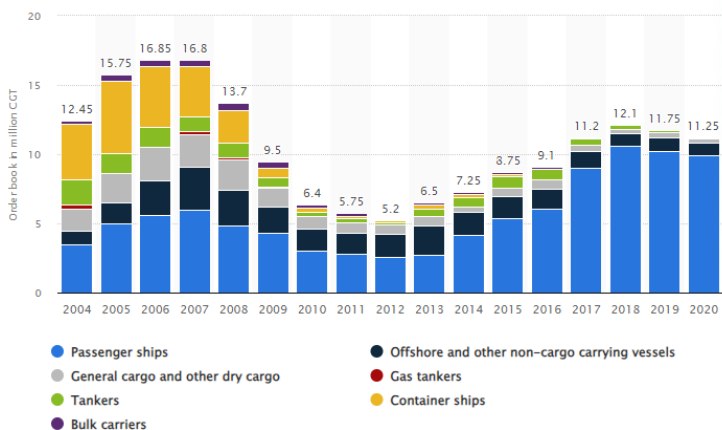
|                             | China         | Japan        | Republic of Korea | Philippines | Viet Nam   | Europe       | Rest of the world | World total  | Percentage share |
|-----------------------------|---------------|--------------|-------------------|-------------|------------|--------------|-------------------|--------------|------------------|
| Bulk Carriers               | 11 233        | 5 360        | 443               | 344         | 98         |              | 17 477            | 31.4         |                  |
| Oil Tankers                 | 4 203         | 1 745        | 8 294             |             | 318        | 157          | 10 14 727         | 26.5         |                  |
| Containerships              | 5 361         | 1 487        | 3 263             | 50          |            |              | 44 10 205         | 18.4         |                  |
| Gas Carriers                | 899           | 268          | 3 665             |             |            | 7            | 4 838             | 8.7          |                  |
| Ferries and Passenger Ships | 391           | 84           | 4                 | 2           | 5          | 2 028        | 65 2 580          | 4.6          |                  |
| General Cargo               | 1 793         | 216          | 52                |             | 1          | 75           | 118 2 255         | 4.1          |                  |
| Offshore                    | 1 240         | 5            | 184               | 0           | 21         | 39           | 230 1 720         | 3.1          |                  |
| Chemical Tankers            | 614           | 326          | 343               |             |            | 26           | 36 1 345          | 2.4          |                  |
| Other                       | 160           | 96           | 5                 |             | 0          | 131          | 39 431            | 0.8          |                  |
| <b>Total</b>                | <b>25 895</b> | <b>9 585</b> | <b>16 254</b>     | <b>396</b>  | <b>444</b> | <b>2 464</b> | <b>542 55 580</b> | <b>100.0</b> |                  |
| <b>Percentage share</b>     | <b>46.6</b>   | <b>17.2</b>  | <b>29.2</b>       | <b>0.7</b>  | <b>0.8</b> | <b>4.4</b>   | <b>1.0</b>        | <b>100.0</b> |                  |

Source: UNCTAD calculations, based on data from Clarksons Research, 2023.

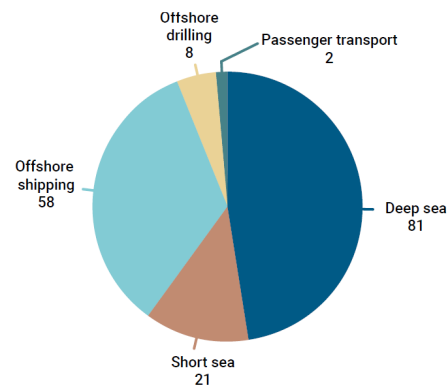
Notes: Propelled seagoing merchant vessels of 100 GT and above. See also <http://stats.unctad.org/shipbuilding>.

Over the years, Europe continues to grow in the passenger and NCC vessel markets, with passenger vessels comprising around 88% of the EU orderbook as of 2022.

Non-cargo carrying vessels (fishing vessels, research vessels, tugs, dredgers, and other specialized vessels) that focus on offshore, short-sea, and deep-sea missions are considered big segments in the future.



Number of new ships that shipowners anticipate building in the coming five years

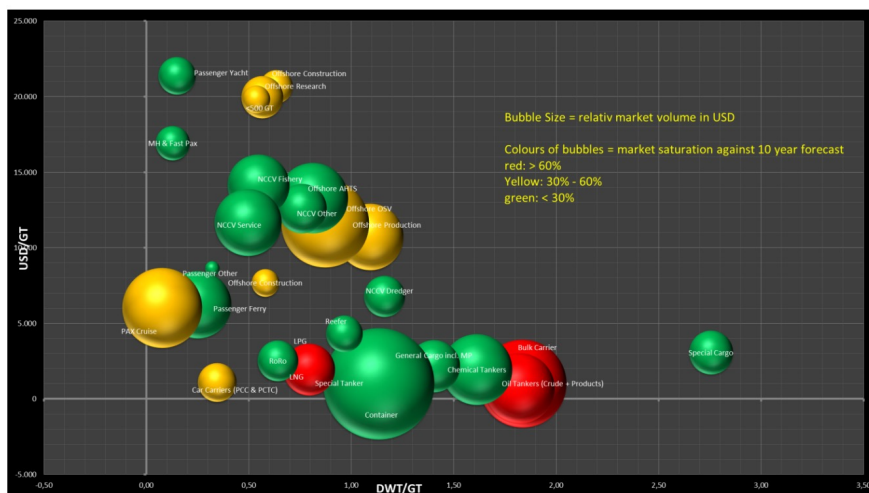


(Statista, 2023 [69])

(Norwegian Shipowners' Association, 2022 [70])

Although the number of newly constructed ships produced by European yards is relatively low, they still constitute a significant percentage of global new orders market value.

Based on Clarkson Research, Europe was responsible for 55% of the total value in global new orders in 2016, primarily due to its focus on building expensive, specialized, and customized ships (SEA Europe, 2017 [11]).



Shipbuilding market forecast 2016-2025 (BALance Technology Consulting, 2017 [71])

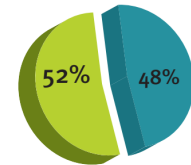
**Due to continuous investments in complex vessels and Research and Development (R&D), European Original Equipment Manufacturers (OEMs) are the largest marine equipment suppliers worldwide.**

European companies supply about 52% of the maritime equipment worldwide. From 2010-2014, the average production value was around 71.3 billion euros.

**EUROPEAN MARINE EQUIPMENT MANUFACTURERS & SUPPLIERS:  
A world market leader**

- ▶ ± 22,000 big, small or medium-sized marine manufacturers and suppliers.
- ▶ Deliver various materials, systems and equipment or act as service providers in engineering and consulting.
- ▶ Generate an annual turnover of about € 60 bn.
- ▶ Employ more than 350,000 people directly.
- ▶ Represent 50% of the worldwide market share.
- ▶ Invest 9% of the industry sales in research, development and innovation, i.e. amongst the highest investment intensity in RDI activities in Europe.

Equipment Suppliers Market Shares  
Global production volume average = € 125.5 bn



■ European companies supplied volume (EU28+Norway)  
■ RoW supplied volume

(OECD, 2023 [67]) and (SEA Europe 2017 [11]), Adopted from (BALance Technology Consulting (2017) [51])

**European shipyards have adapted to new demands by offshoring the construction of certain ship parts to keep costs low, allowing them to focus on complex outfitting and repairs.**

For instance, in the North Sea, yards focus on ship repair and new builds. About 8% are scrapping shipyards.

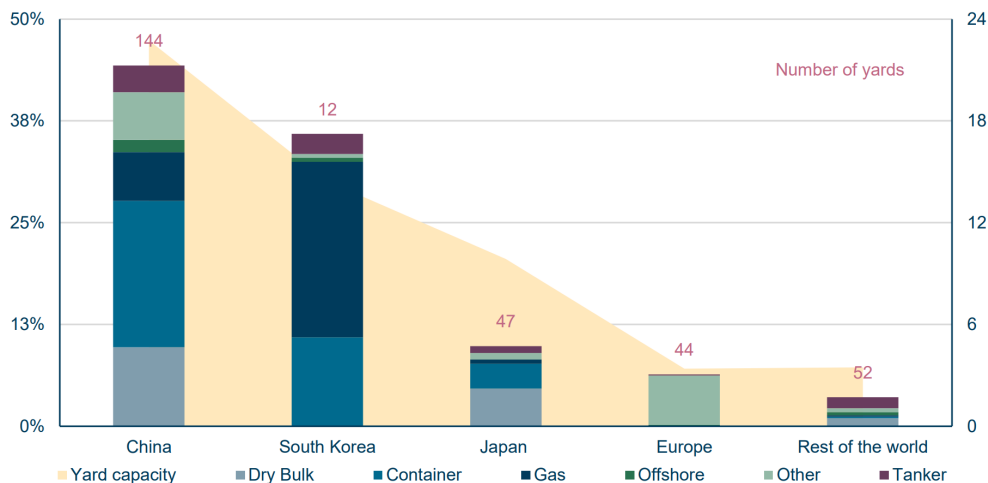


(Trusted Docks, 2023 [12])

**There are about 150 yards in Europe and roughly 40-50 (first-tier yards) are active in global market for large seagoing commercial vessels, comprising 7% of global yard capacity.**

These first-tier yards manage to utilize up to 80% of their capacity in 2022. Capacity dropped in 2023 due to long building periods but a 105% utilization demand is expected in 2024. **This high yard utilization demands high-efficiency yard planning.**

Share of global orderbook (%) and yard capacity (million cgt)



(Danish Ship Finance, 2023 [13])

**Global Shifts and Sustainability Goals also increase the overall uncertainty and volatility in the market.**

UNCTAD's Uncertainty Factors related to the maritime industry are driving changes not only in regulatory maritime policy but also in influencing ship demands and maritime solutions.

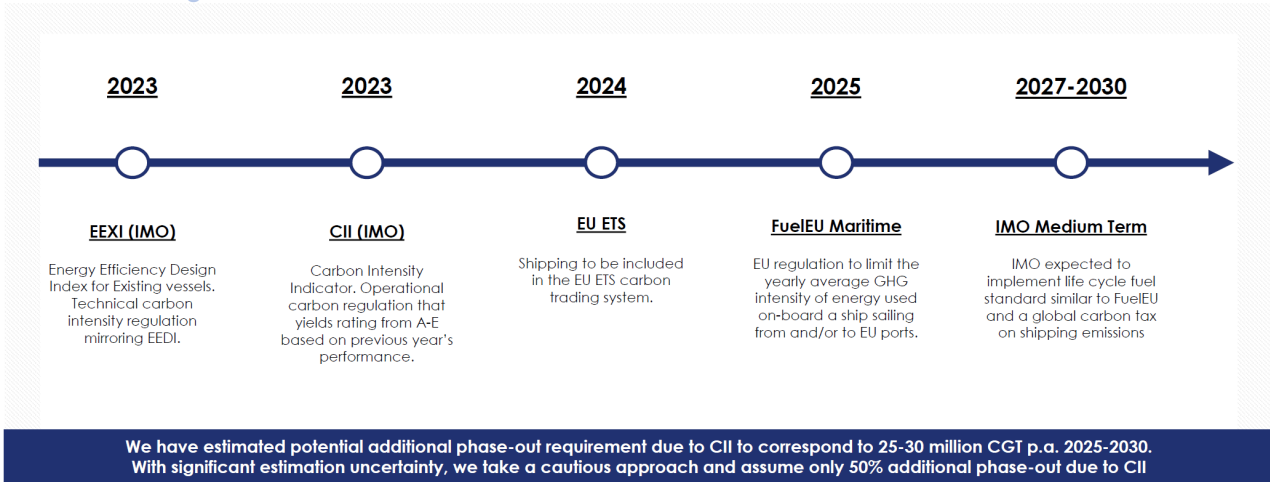
| Geopolitics and Trade Dynamics   | Environment   | Industry 4.0 Trends   |
|--|---|---|
| US-China Trade Tensions affecting tariffs<br>Race for Arctic Resources<br>Tension in Maritime<br>Chokepoints Structural shifts in globalization patterns | Accelerating environmental and regulatory agenda<br>Melting of Polar Caps<br>Rising Sea Level<br>Ocean Acidification<br>Ocean Pollution (and the subsequent effects on food supply)<br>GHG Emission | Automation and Robotics<br>Internet of Things (IoT)<br>Big Data, ML/AI<br>Advanced Materials<br>Biotechnology<br>Renewable Energy |

Adopted from (UNCTAD, 2019 [14])

**Due to increased focus on environmental regulations, a large portion of today's fleet may be part of the future's demolition pool.**

Clarkson Research has estimated that about 30 to 40% of today's yard capacity is needed to decarbonize the fleet.

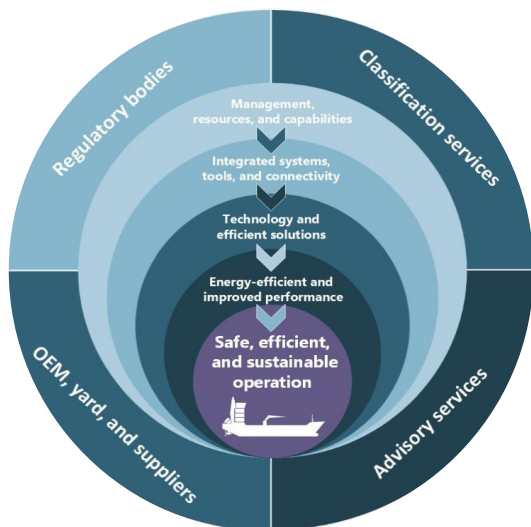
**Environmental Regulations:**



(Clarksons, 2023 [68])

**Maritime rules and regulations are not only governed by global regulatory bodies (such as IMO) but also by Classification Societies.**

Class Societies, selected based on flag state requirements, are organizations that develop and apply technical standards for ship design, construction, survey, and inspection.



**Classification Societies:**



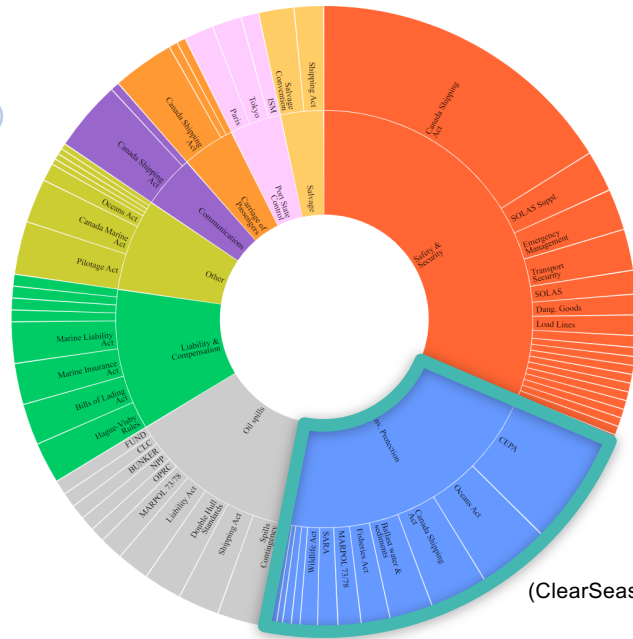
**These shifting maritime laws and regulations mean design thresholds related to safety and the environment change year after year.**

Designers must stay up-to-date with policies as work templates and reference designs may not always be transferrable.

**Example: Regulatory Considerations (Canada)**

Environmental Pollution regulations that may affect ship layout, tankage arrangement, etc.:

- CEPA
- Oceans Act
- Canada Shipping Act
- Ballast Water and Sediments
- MARPOL 73/78
- SARA
- Wildlife Act



(ClearSeas, 2023 [72])

**In summary, the European SD&SB market is faced with a few unique features:**

- Industry is designed to maximize **custom and specialized ships** (from OEMs to ship-type investments) which requires a high degree of systems integration in both design and construction
- Extreme **multi-organization** with yards abroad requires high collaboration and robust data security
- **Limitations in shipyard capacity and yard utilization** require specialized facility planning
- **A unique maritime ecosystem** means that the European market is well-placed to tackle sustainability challenges and explore innovative market segments but needs low-risk strategies to do this

| Strength   | Weakness   |
|--|--|
| <ul style="list-style-type: none"> <li>• Level of innovation</li> <li>• Innovative SMEs and strong position of marine equipment industry</li> <li>• Strong linkages between yards and Marine equipment</li> <li>• Efficiency</li> <li>• Specialisation in niche markets</li> <li>• Spillovers between defence and commercial segments</li> </ul> | <ul style="list-style-type: none"> <li>• Cost levels</li> <li>• Access to skilled labour</li> <li>• Potential difficulties in knowledge protection (especially among SMEs)</li> <li>• Fragmented government responses</li> </ul>   |
| Opportunities  | Threats  |
| <ul style="list-style-type: none"> <li>• New segments, continuous innovation</li> <li>• Greening of shipbuilding industry</li> <li>• Existing transport policies (greening of transport, increased transport quality)</li> <li>• Enhanced requirements regarding shipping standards</li> </ul>   | <ul style="list-style-type: none"> <li>• Demand shift from EU to Asian buyers</li> <li>• Strengthening of Asian maritime cluster</li> <li>• Increasing development of marine equipment industry</li> <li>• Competitors moving up the ladder</li> <li>• SME's not surviving the crisis</li> <li>• Flexible and swift competitor's governments to support their industry</li> <li>• Critical mass required to maintain/refresh high skilled workforce. Europe may be too small compared to competitors. Ageing workforce</li> <li>• Price competition in light of economic crisis</li> </ul> |

(Thamby, 2023 [26])

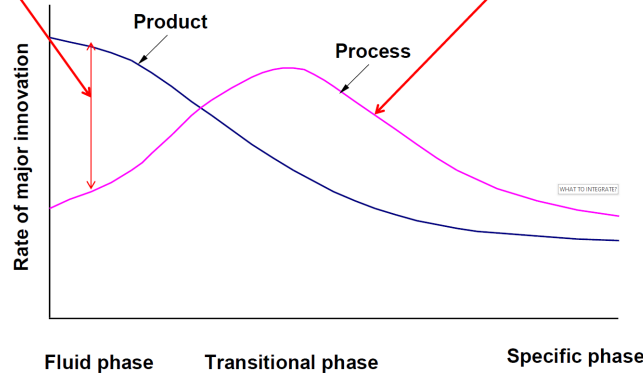
## How can European SD&SB remain innovative but also increase production efficiency?

As the Production Efficiency curve suggests, trade-offs between product innovation and process efficiency exist. Is there an optimal set of conditions that can enable high product innovation and process efficiency for the European market?

### The "production efficiency escape" gap

- This is where we want to be
- Product is key, not production efficiency
- (But can't be too inefficient!)

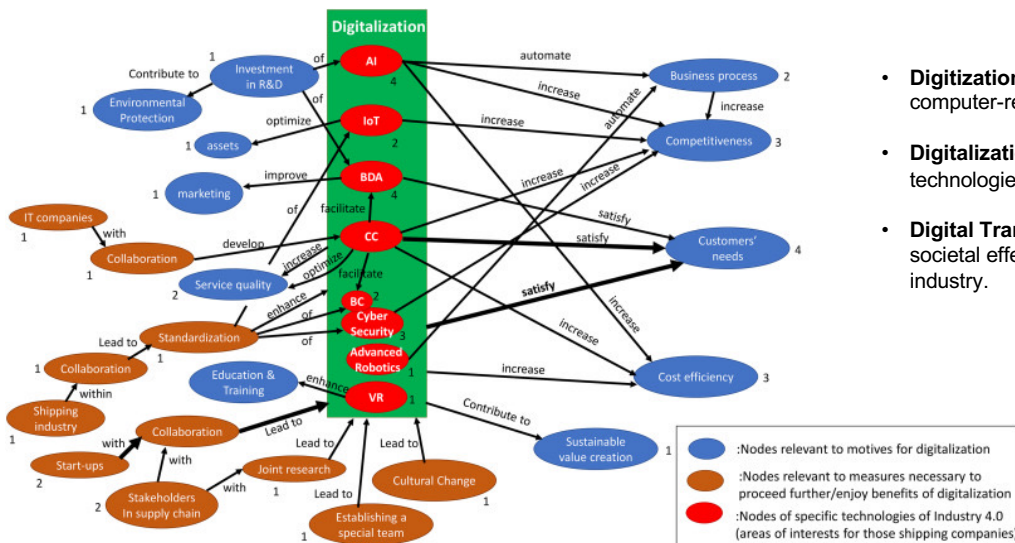
High volume shipbuilding is here.



(Koenig, 2019 [30])

## Awareness of the benefits of digitalization has increased to handle the rising design and construction complexity and business uncertainty in the SD&SB market.

The motivation behind digitalization ranges from increasing business competitiveness to asset reliability, which includes the need for advanced manufacturing and operational solutions.

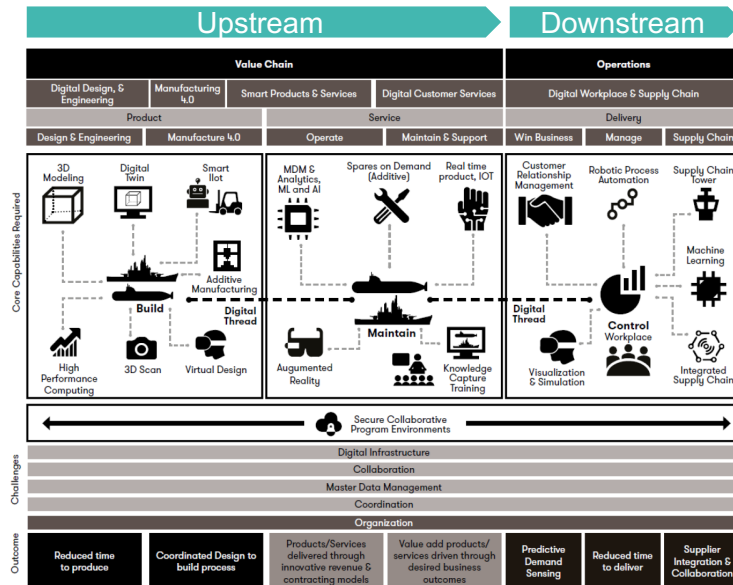


(Ichimura, et al., 2022 [73])

- **Digitization:** the conversion of information into a computer-readable format.
- **Digitalization:** the use of digital technologies to optimize business processes.
- **Digital Transformation:** the total and overall societal effect of a widespread digitalization of the industry.

Definitions adopted from naval-architect.io

Studies and assessments show that there are multiple opportunities for process improvement with digitalization across the ship's lifecycle, from ship design to operations.

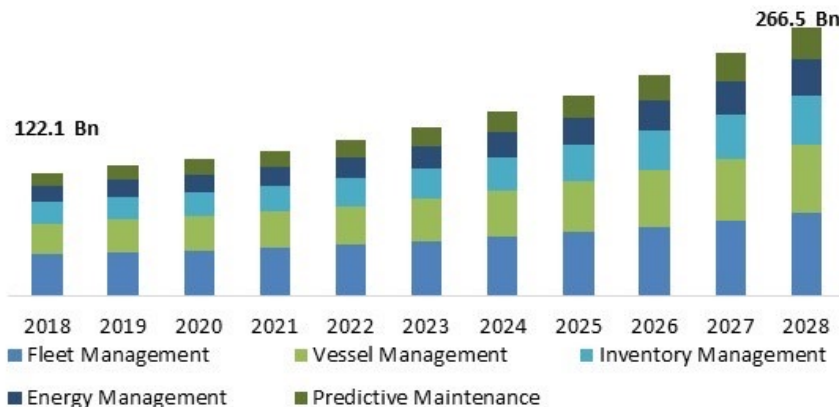


(Spoehr, et al., 2021 [74])

**Business Opportunities:** There is a projected market of up to 5.5 billion USD by 2030 on maritime digitalization, especially in digital shipyards. These solutions cover vessel management and predictive maintenance.

European interest in digitalization can be attributed to the large number of OEMs already present in the region, which are themselves facilitating advanced digital solutions for their equipment.

**Maritime Digitization Market Size, By Application, 2018 - 2028**

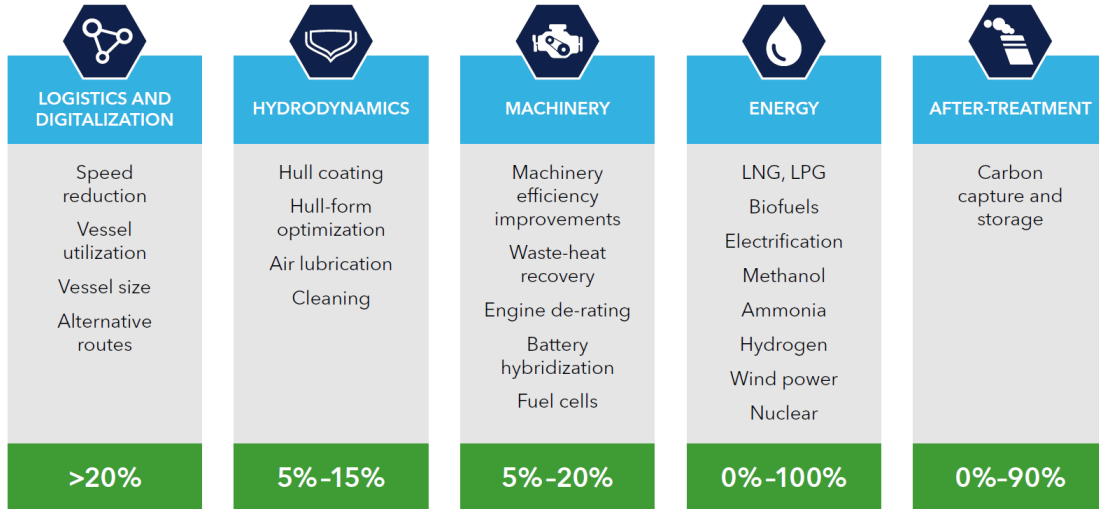


(KBVResearch, 2023 [16])

**Sustainability Opportunities: The improvements in operational efficiency and logistics can enable ships to be more sustainable.**

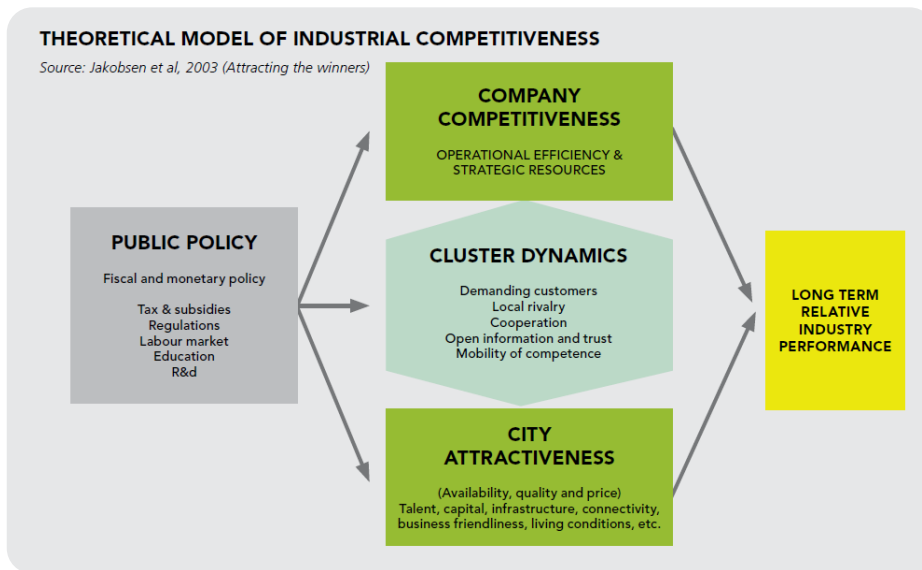
Up to 20% of fuel savings can be attained with better vessel utilization and alternative route planning.

**DNV-GL's Areas of Improvement to meet Sustainability Goals**



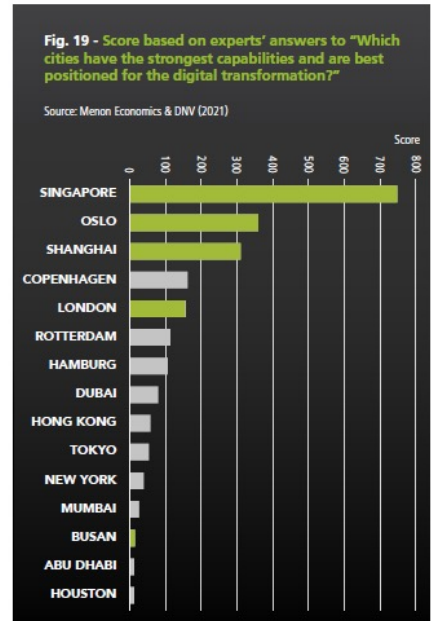
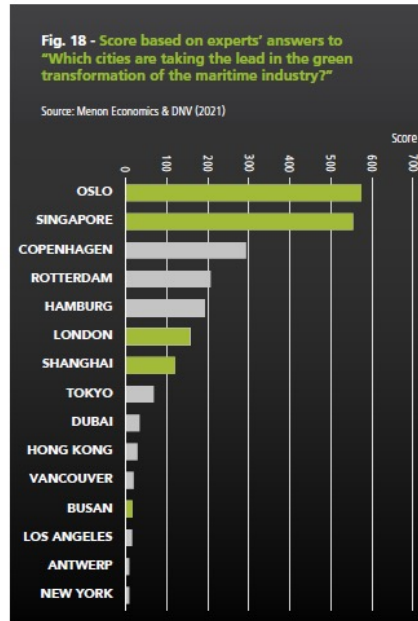
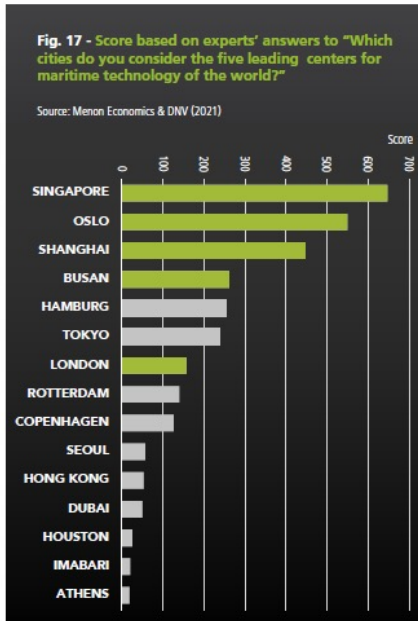
(DNV, 2023 [15])

**Why clusters are important? Clusters are a group of industries that are directly and indirectly tied to an industry within a geographical area. These clusters help to drive and facilitate innovation.**



(Menon Economics, 2022 [75])

## European clusters and cities are globally perceived to be leaders in digitalization and are well-positioned for transformation.



(Menon Economics, 2022 [75])

## EU Place in Shipbuilding Market: Section Summary

Unique features of the European SD&SB market:

- Industry is designed to maximize **custom and specialized ships** (from OEMs to ship-type investments) which requires a high degree of systems integration in both design and construction
- Extreme **multi-organization** with yards abroad requires high collaboration and robust data security
- **Limitations in shipyard capacity and yard utilization** require specialized facility planning
- **A unique maritime ecosystem** means that the European market is well-placed to tackle sustainability challenges and explore innovative market segments but needs low-risk strategies to do this

Opportunities in digitalization:

- Maritime digitalization can help to **drive business competitiveness and meet global sustainability goals**
- The European maritime cluster and ecosystem is perceived to be **well-positioned to tackle digital transformation**

## References for EU Place in Shipbuilding Market

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## References for EU Place in Shipbuilding Market

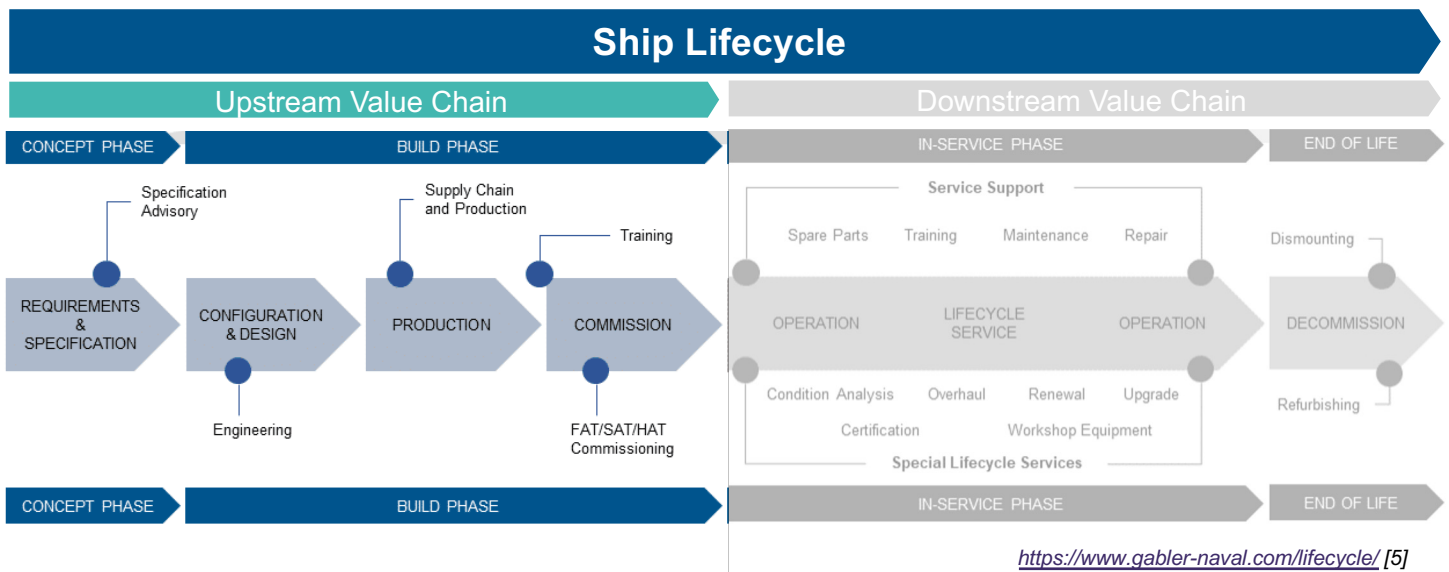
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## Best Practices on Ship Design and Shipbuilding: Outline

1. EU Shipbuilding and the SEUS Project
2. EU Place in Shipbuilding Market
- 3. The Ship Design and Shipbuilding Process**
4. Multi-domain Taxonomy
5. The Ship Design and Shipbuilding Toolbox
6. Distinctions in Ship Design and Shipbuilding
7. Single Source of Truth Concept or Attempt

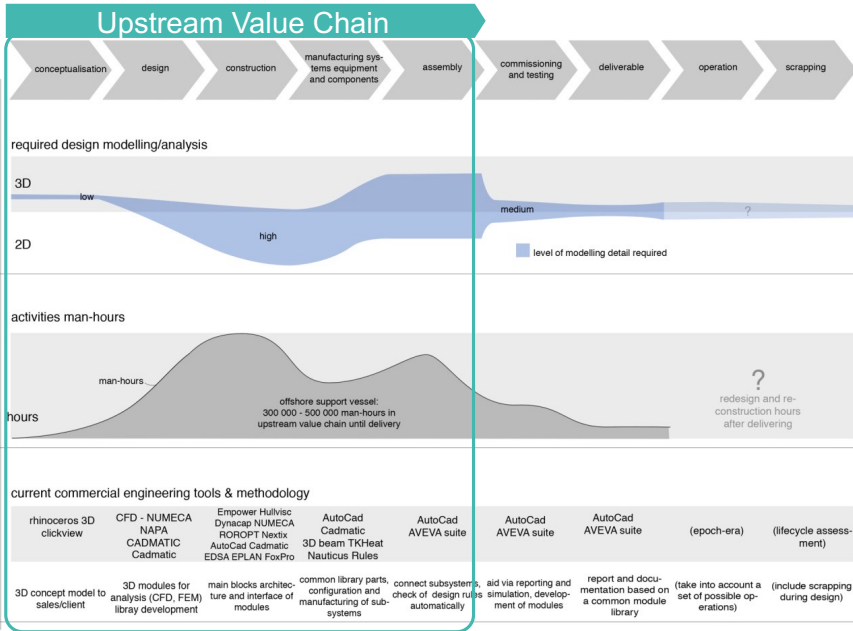
## Recall: SD&SB Industry covers a wide range of services and activities throughout a vessel's lifecycle.

Given that the SEUS' project focus is on the upstream value chain, the Ship Design (concept and detailed engineering) and Shipbuilding (Construction) phases are explored in this section.



<https://www.gabler-naval.com/lifecycle/> [5]

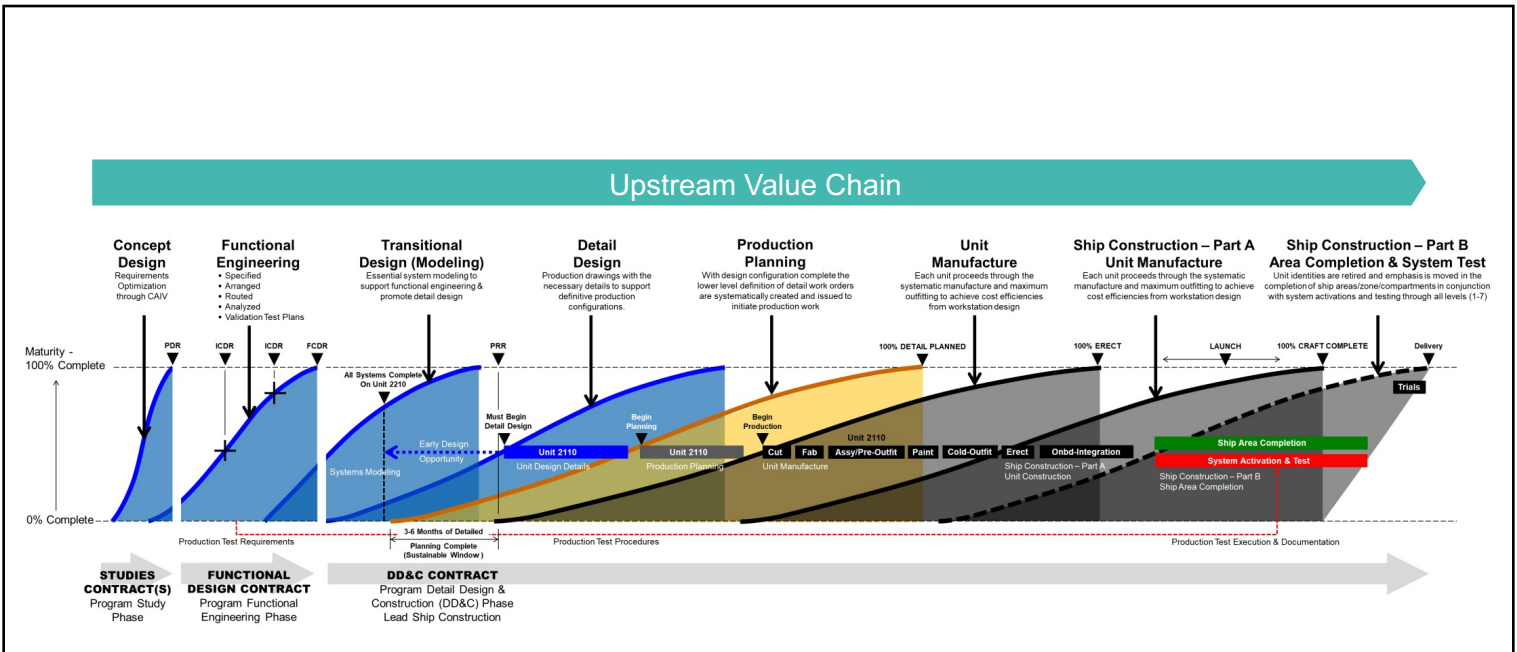
Compared to the downstream value chain, the ship upstream activities are cost-intensive due to the level of engineering and labor required.



Where the upstream stages are broken down into:

1. Concept Design (covering preliminary ship design)
2. Detailed Engineering (covering contract and functional engineering)
3. Intermediate Engineering (or production engineering)
4. Steel Construction
5. Parts Fabrication
6. Outfitting (covering on-block and onboard outfitting)
7. Launching
8. Delivery and Testing
9. Commissioning

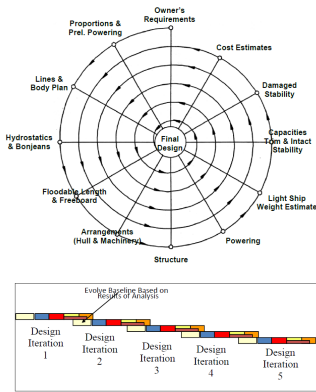
(Ulstein, 2015 [76])



(Hitchcock, 2023 [77])

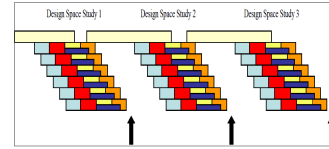
Ship design involves several design iterations, from preliminary concept design to detailed engineering, intended to converge into a design that suits the client's needs. For custom designs, ship design begins with requirement elucidation and ensuring that the vessel can perform the expected operations or Ship Mission.

There are several approaches to ship design, from the traditional Design Spiral to more modern approaches such as model-based and set-based design.

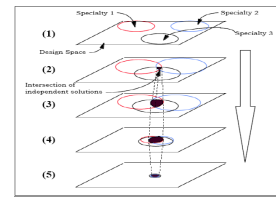


**Classic Design Spiral (Andrews 1981)**  
(Development and refinement of a single design, ~up to 8-12 weeks per design iteration)

(NAVSEA, 2012 [20])



**Synthesis Model-based Design Optimization**  
(Multiple designs developed and tested concurrently, high computing requirements)



**Set-based Design (Bernstein 1998)**  
(Design exploration divided into teams based on systems, Most commonly practiced today, high collaboration)

At each ship design cycle/iteration or model, naval architects and designers assess critical ship features and perform design activities.

However, these activities are not always performed linearly.

### Common Ship Design Activities

#### Hydrostatics:

- Ship Weight Estimation and Area/Volume Assessment (Will it float?)
- Intact Stability Assessment (Will it float upright?)
- Damage Stability Assessment (Will it sink in case of damage?)

#### Hydrodynamics:

- Propulsion Trade-off Analysis (How will it sail?)
- Vessel Performance Evaluation (Will it be able to perform its mission?)
- Electric Load Assessments (Will it have enough power to sail and perform its mission?)

#### Others:

- General Arrangement (GA) Drawings (Will everything fit inside the hull and structure?)
- Safety Compliance Review (Can it perform its mission and sail safely and meeting international regulations?)

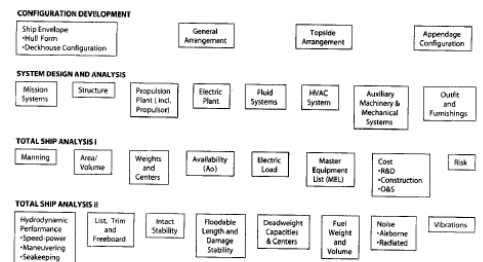
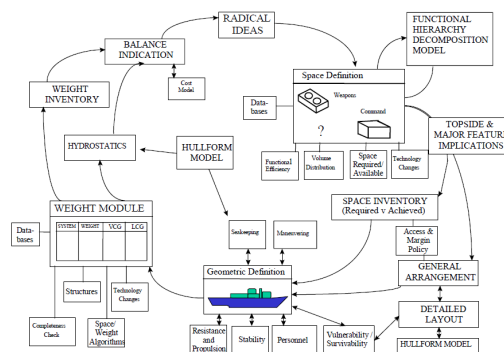


Figure 5.8 Concept Design Task Categories



(Andrews, et al., 2006 [78])

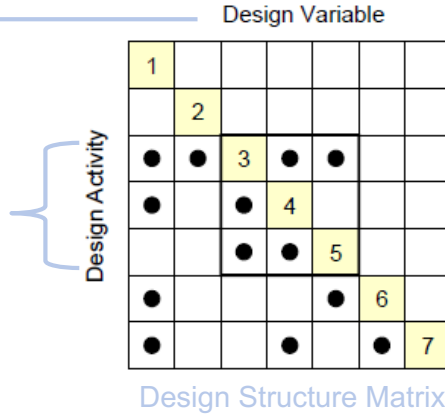
In the early stages of design, automated methods with low-fidelity data can be used for the systematic exploration of the design space. However, decision-making itself at this stage can't be automated due to close client collaboration and the lack of design information. Flexibility and collaboration are key in early Concept Design.

To manage multiple engineering variables and cost estimates related to ship design, naval architects and marine engineers need to understand various design trade-offs (via design matrix or similar).

Example: Ship Speed as a Design Variable

Ship Speed affects several Design Activities, like:

- Vessel Range & Endurance
- Vessel Propulsion System
- Fuel Capacity
- Volume and Area of Machinery Spaces (affecting GA & layout)
- Volume and Area of Tankage (affecting Stability and Weight)
- Overall Costs



(Doerry, 2009 [79])

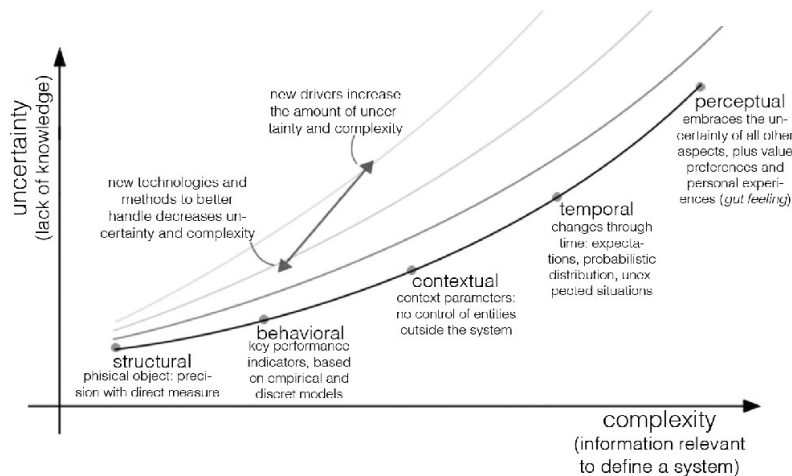
**Design trade-offs:**

- Lower Costs vs Improved Vessel Performance & Mission Capabilities
- Simplified Hull form vs Increased Ship Stability
- Simplified Structure vs Increased General Arrangement (GA) flexibility
- Increased Structural Complexity vs Lower Weight

**New consideration: Greener Ship Design**

Due to the interactions between Design Activities, ship design especially at the Concept Design stage is highly complex due to dependencies between parts (or combinatorial complexity) and due to uncertainty.

Uncertainty in ship design covers not only structural or technical uncertainty but also ship behavioral uncertainty and contextual uncertainty.



(Gaspar, 2013 [21])

To drive effective decision-making, reference (historical or analogous) data and contextual knowledge are critical in the Concept Design stage. Errors in this stage are cheaper to amend.

Risk margins and adjustment factors are commonly used at early design to manage the lack of certainty. Rule-of-thumb thinking, and experience become highly relevant, as opposed to theoretical design thinking which can be time-consuming and costly to implement.

Example: How to estimate ship weight with ~700 components (excluding steel parts)?

Analogous Estimate

Historical data on one analogous system or subsystem (with adjustment factors)

Parametric Estimate

Statistical analysis of historical projects (with weight ratios or derived equations)

Engineering Estimate

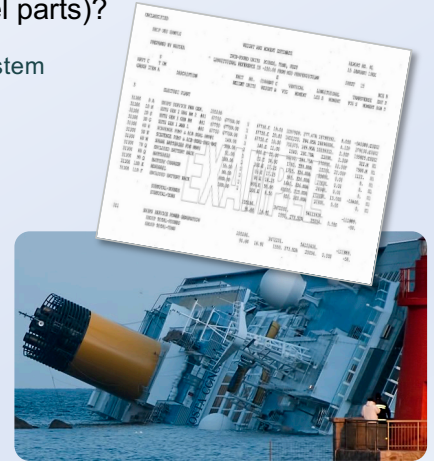
Bottom-up detailed estimate (Too time-consuming)

Actual Costs

Documented cost of a built ship of the same design (Not available)

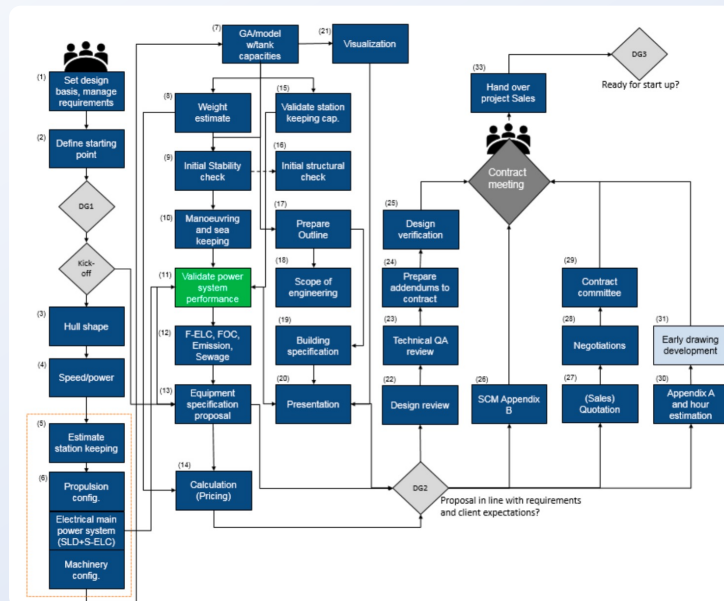
What happens if the weight estimate is completely erroneous and how can we know?

Restart design loop? More costly if unseen in the future:



## Concept Design – Sample Process Execution

### Concept Design Stages at Ulstein



(Hovden, 2018 [22])

NOTE: These process maps are interpretations of the ship design (concept phase) logic and may vary from company to company.

## A team in the Concept Design Stage sees:

**Ship AS Complex System of Systems (SoS) with plenty of converging and conflicting design requirements.**

**Main Goal of ship designers:** Use strategic (often risk-based) decision-making to arrive at a competitive and feasible ship design that meets client's requirements

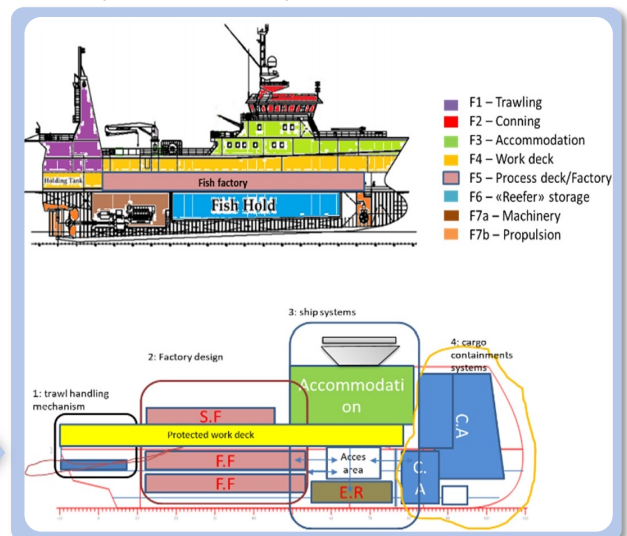
### Information:

- Data is critical but low-fidelity information is typically available
- Lots of uncertainty from missing data, from client, from interdisciplinary team members
- Heavy reliance on contextual knowledge

**When the high-level concept is defined, further granularity in design definition and evaluation is performed in the Detailed Engineering stages. Unlike Concept Design, there is less uncertainty in the design and there is a shift in focus to ensuring feasibility is assessed and details are complete.**

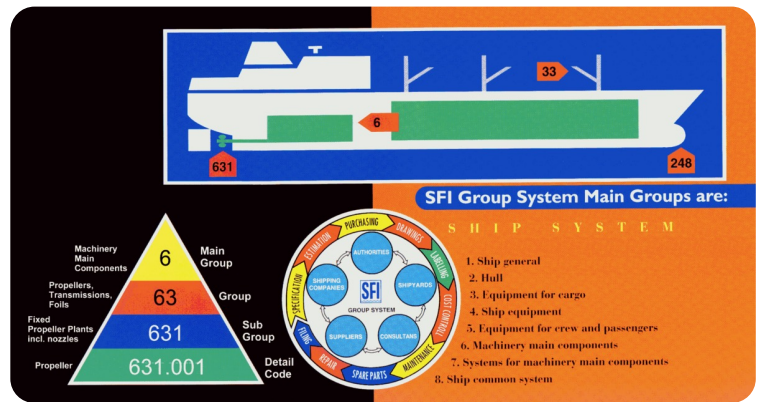
To handle the complexity of a vessel, the ship is often broken down by function or systems.

| Level of complexity | Technical system                | Characteristics  | Marine examples  |
|---------------------|---------------------------------|--|--|
| I (simplest)        | Component                       | Elementary parts whose manufacturing does not include assembly.  |  |
| II                  | Mechanism, sub-assembly         | Parts consisting of a number of components, contributing to simple functions.  |  |
| III                 | Machine, equipment              | Systems that perform a closed function.  | Propulsion system, marine machinery, topside equipment (cranes, winches, etc). |
| IV                  | System                          | System that encapsulates different machines, equipment, and sub-systems, each fulfilling a function towards a common "functional and spatial unity" (Magee & de Weck, 2007). | Ship, marine structures, subsea systems, etc.                                  |
| V                   | Super-system, system-of-systems | Higher-order systems, due to the existence of common functional unity across several Level IV systems, possibly with operational and managerial independence (Maier, 1998).  | Fleet, marine transport system, offshore oil and gas infrastructure, etc.      |



Ship breakdown standards such as Ship Work Breakdown Structure (SWBS) and SFI are commonly utilized and have been in use since the 1980s.

| ESWBS Group | Description                         |
|-------------|-------------------------------------|
| 000         | General Guidance and Administration |
| 100         | Hull Structure                      |
| 200         | Propulsion Plant                    |
| 300         | Electric Plant                      |
| 400         | Command and Surveillance            |
| 500         | Auxiliary Systems                   |
| 600         | Outfit and Furnishings              |
| 700         | Armament                            |
| 800         | Integration/Engineering             |
| 900         | Ship Assembly and Support Services  |



(SpecTec, u.d. [80])

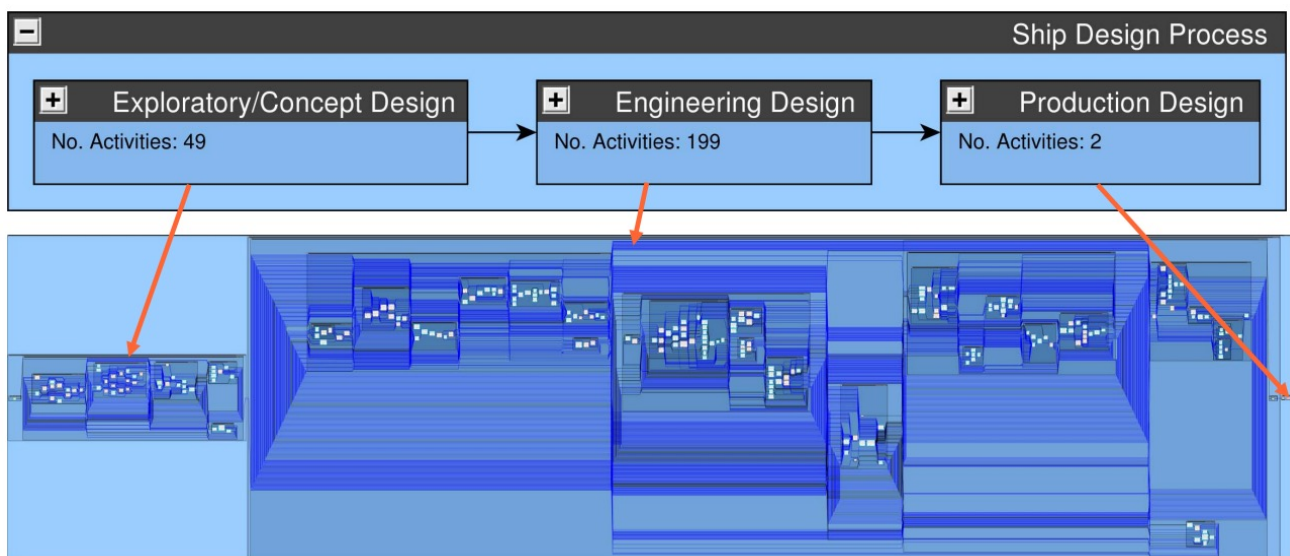
### SWBS Breakdown

Developed in the 1970s to manage US Navy ship systems  
Up to ~900 components can be defined

### SFI Breakdown

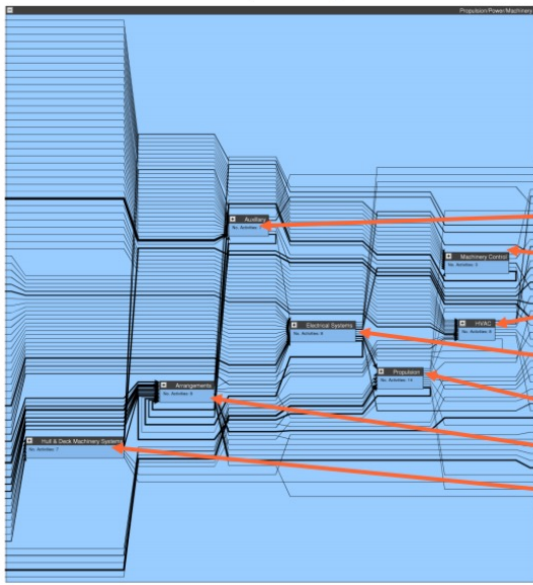
Developed in the 1970s to be a common code for maritime and offshore rigs  
Up to ~700 components can be defined

At Detailed Engineering stage, various design analyses and evaluation are performed, often concurrently among different teams to manage all the required systems that need to be evaluated.

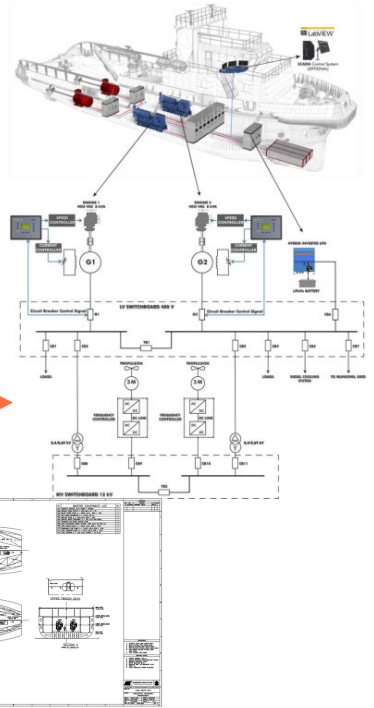
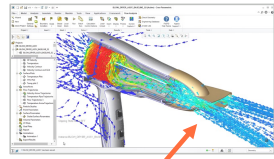


(NAVSEA, 2012 [20])

Example concurrent workflow for SWBS 299, 300,500:



1. Auxiliary Systems
2. Machinery Control
3. HVAC (Heating, Ventilation, Air Conditioning)
4. Electrical Systems
5. Propulsion
6. Machinery Arrangements
7. Hull & Deck Machinery Systems



(NAVSEA, 2012 [20])

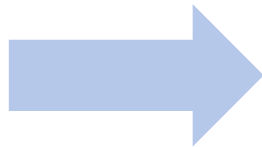
Source (Top, clockwise): Siemens.com, edibon.com, <https://www.cadcrowd.com/>

Common outputs from Concept Design

- Essential performance requirements
- Principal hull dimensions and hull form coefficients (Cp, Cx)
- Area/volume summary
- Configuration sketches: inboard profile and main deck plan
- Payload definition, for example, space, weight, critical dimensions, adjacencies, required support services
- Description of mission-critical systems and features
- Weight/KG estimate, 1-digit level
- Propulsion plant type, installed power, and number of propulsors
- Installed electric generating capacity
- List of major equipment
- Manning estimate
- Speed/power estimate
- Endurance fuel estimate
- Intact stability check
- Estimates of critical performance aspects, as required, e.g., radiated noise or seakeeping
- Cost estimate
- Technical risk assessment and risk management plan

*Technical deliverables increase dramatically during this stage.*

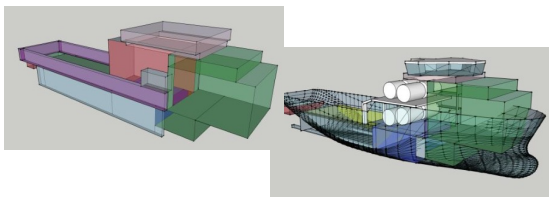
*Each deliverable will also require management, planning, and checking, which inflates the cumulative work hours.*



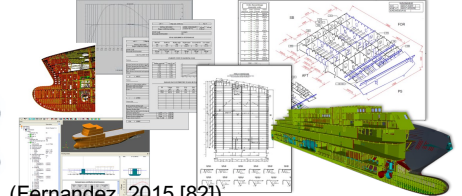
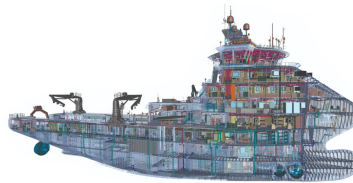
Common outputs from Detailed (Contract) Design

- |  |   |  |
|--|---|--|
| <ul style="list-style-type: none"> <li>Ship specification</li> <li>Lines drawing</li> <li>Appendage drawing</li> <li>General arrangements (outboard profile, inboard profile, all decks and holds)</li> <li>Topside arrangement</li> <li>Capacity plan</li> <li>Weight report (3-digit level, KG and LCG, 20-station weight distribution, gyradii)</li> <li>Structural design criteria manual</li> <li>Midship Section</li> <li>Steel scantling drawings (decks, bulkheads, shell expansion, typical sections, deckhouse)</li> <li>Machinery control system diagrams</li> <li>Propulsion and auxiliary machinery arrangement drawings (plan views, elevations, and sections)</li> <li>Propulsion shafting arrangement</li> <li>Propeller design</li> <li>Electric load analysis</li> <li>Electric power and lighting systems - One line diagrams</li> <li>Fault current analysis</li> <li>Navigation system diagram</li> </ul> | <ul style="list-style-type: none"> <li>HVAC load analysis and design criteria</li> <li>Ventilation and air conditioning systems diagrams</li> <li>Piping systems analysis</li> <li>Diagrammatic arrangements of all piping systems</li> <li>Fire control diagram by decks and profile</li> <li>Mechanical systems arrangements, for example, deck, hull and ship control systems</li> <li>Living space arrangements (berthing, messing, sanitary, recreation, etc.)</li> <li>Commissary space arrangements</li> <li>Pilot House, Chart Room, and other working space arrangements</li> <li>Interior communications system diagram</li> <li>Master Equipment List (MEL)</li> <li>Preliminary ship manning document</li> <li>Pollution control systems report</li> <li>Loading conditions</li> <li>Floodable length curves</li> <li>Trim and stability booklet</li> <li>Damage stability analysis</li> <li>Endurance fuel analysis</li> <li>Hydrodynamic model test results, for example, resistance, propeller open</li> </ul> | <ul style="list-style-type: none"> <li>water, self-propulsion, maneuvering, seakeeping, etc and performance assessment reports</li> <li>Stack gas flow analysis</li> <li>Evaluations of other aspects of required performance</li> <li>Availability analysis (Ao)</li> <li>Maintenance Plan</li> <li>Supportability Plan</li> <li>Crew Training Plan</li> <li>T&amp;E Plan</li> <li>Safety analysis</li> <li>Procurement specifications for long-lead-time and other important outfit components, for example, main propulsion engines, diesel generators, reduction gears, anchor windlass</li> <li>Models and Mockups</li> <li>Cost estimate</li> <li>Technical risk assessment and risk management plan</li> <li>Initial regulatory body review</li> <li>Building plan</li> <li>Budget control list (estimated weight of all required material by material family or cost code)</li> <li>Production plan</li> </ul> |
|--|---|--|

(Gale, 2003)

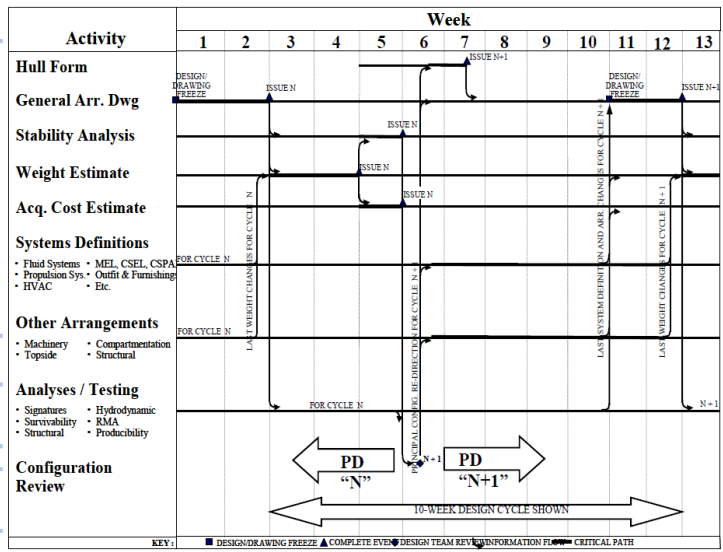


(Vestbøstad, 2011 [81])



(Fernandez, 2015 [82])

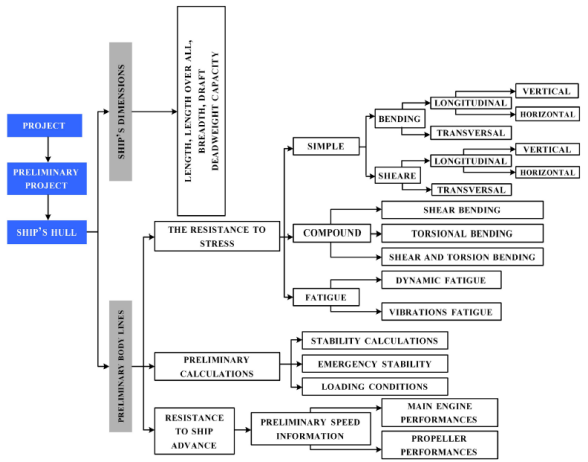
Design work planning and execution at this stage involves the coordination of tasks involved in (a) detailed design definition, (b) design evaluation (quality control and testing), and (c) design compliance (regulatory and specification compliance)



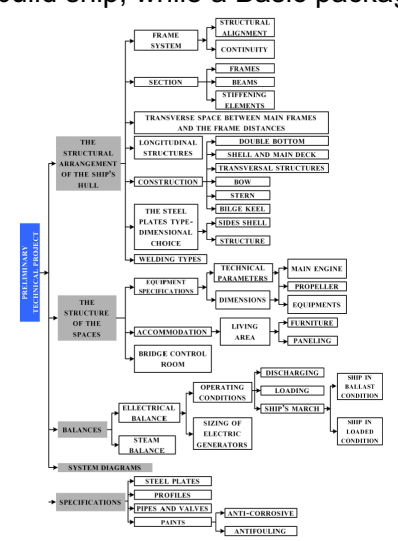
(NAVSEA, 2012 [20])

Alternative project task decompositions may exist depending on the scope of the project and depending on a company's documentation standards.

For example, basic and detailed projects may have varying degrees of engineering work requirements. A Detailed Project Design package may be applicable for ready-to-build ship, while a Basic package is applicable for a ship design proposal.



Basic Project Design

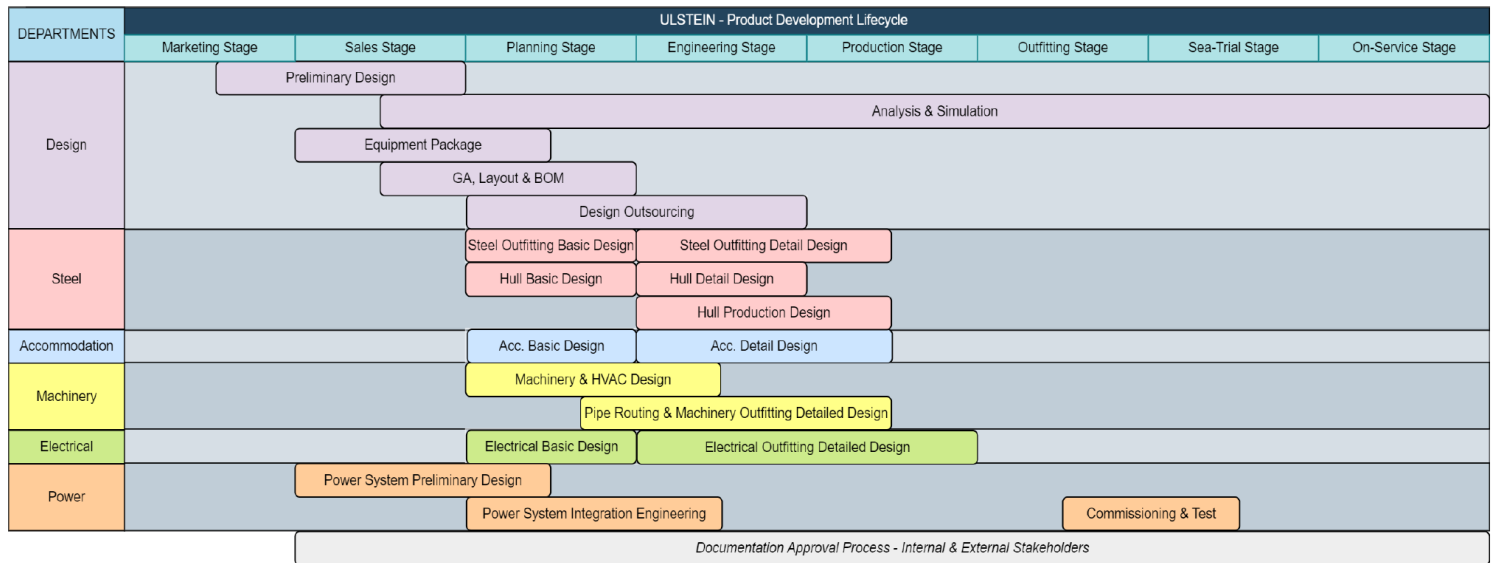


Detailed Project Design

NOTE: These task decompositions are interpretations of what is needed at the detailed design and may vary from company to company.

(Manea & Manea, 2023 [25])

For example, the following timeline and lifecycle incorporates the document approval with the main systems (and task) breakdown from Ulstein:



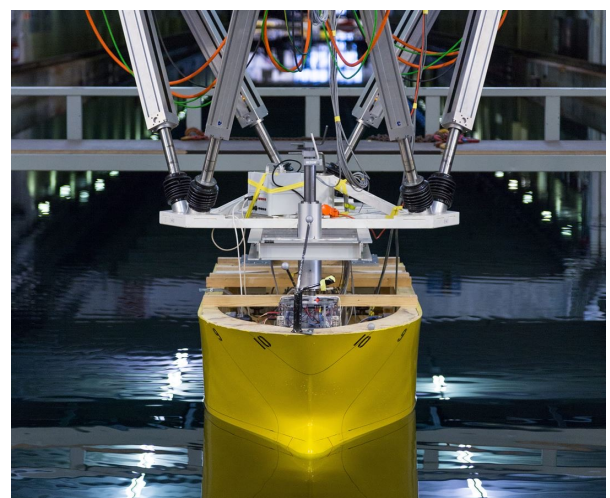
(Thamby, 2023 [26])

NOTE: These task decompositions are interpretations of what is needed at the detailed design and may vary from company to company.

## Design Evaluation Tasks of the design can involve simulation testing and physical testing – from FEA to towing tank testing.

Examples for Hydrodynamics Tests:

|  |  |
|--|--|
| <b>Resistance and Propulsion Tests</b> | <ul style="list-style-type: none"> <li>Determining resistance and propulsion characteristics. It may be important to improve the accuracy of the prediction beyond that estimated using predictive standard series techniques. For some ships, the hull form parameters may be outside of the range of available data and model tests may be particularly important. Appendage details may require investigation.</li> <li>Determining the impact of changes, comparing alternative hull forms, or optimizing the hull for a particular purpose. Selecting final bulbous bow characteristics to suit various operating conditions may require comparative tests.</li> <li>Improving the level of confidence in a powering prediction. This could be desirable for many reasons, including the selection of a specific diesel engine or gas turbine.</li> </ul>                           |
| <b>Propulsor Tests</b>                 | <ul style="list-style-type: none"> <li>Evaluating wake characteristics of the hull to assist in propeller design and optimization.</li> <li>Evaluating alternative propulsors or improving the accuracy of propulsor efficiency predictions.</li> <li>Determining propulsor cavitation or noise characteristics. For some ships where these characteristics are KPPs, such tests may be essential to confirming such performance.</li> </ul>   |
| <b>Maneuvering Tests</b>               | <ul style="list-style-type: none"> <li>Determining the maneuvering characteristics. This may be particularly important for hull forms that have unusual proportions for which prediction techniques are not accurate. Also, ships that conduct alongside operations such as underway replenishment maneuver in very confined areas or have particularly demanding maneuvering requirements. They may require tests where predictions are not accurate or a higher degree of accuracy is required.</li> <li>Evaluating alternative control surfaces relative to maneuvering requirements.</li> </ul>  |
| <b>Ship Motions Tests</b>              | <ul style="list-style-type: none"> <li>Predicting accelerations, periods, and magnitudes of motions. Unusual hull forms or characteristics may require tests to accurately determine the range of accelerations. This could be to assess operating limits, to provide structural or system design information, or to support HSI objectives.</li> <li>Predicting slamming characteristics.</li> </ul>  |
| <b>Special Hydrodynamic Tests</b>      | <ul style="list-style-type: none"> <li>Determining astern powering or stopping characteristics.</li> <li>Flow visualization. This may be needed to align appendages, or for special mission ships, to assist in minimizing hydrodynamic noise.</li> <li>Fin stabilizer alignment.</li> <li>Determination of propeller-induced vibratory forces.</li> <li>Shaft and strut alignment.</li> <li>Topside airflow.</li> <li>Dynamic Stability. The increasing interest in dynamic stability and unusual hull forms may require tests to assess stability characteristics in special conditions.</li> <li>Examining special hydrodynamic phenomena. An example of this might be the behavior of water within a well under specific conditions.</li> <li>Determining structural loads. These may be required for structural design purposes or to investigate operating constraints.</li> </ul> |



Towing Tank Tests  
(sintef.no)

(NAVSEA, 2012 [20])

In addition to technical testing, design compliance and review are critical to ensure that the ship can get class approval for operations, meet pollution requirements, and satisfy clients' needs.

In addition to the Classification Society's Approval (Class Approval) upon review, ships may also require additional certificates. Each certificate will have its unique requirements. Regulatory bodies will inspect that the ship is compliant with these requirements.

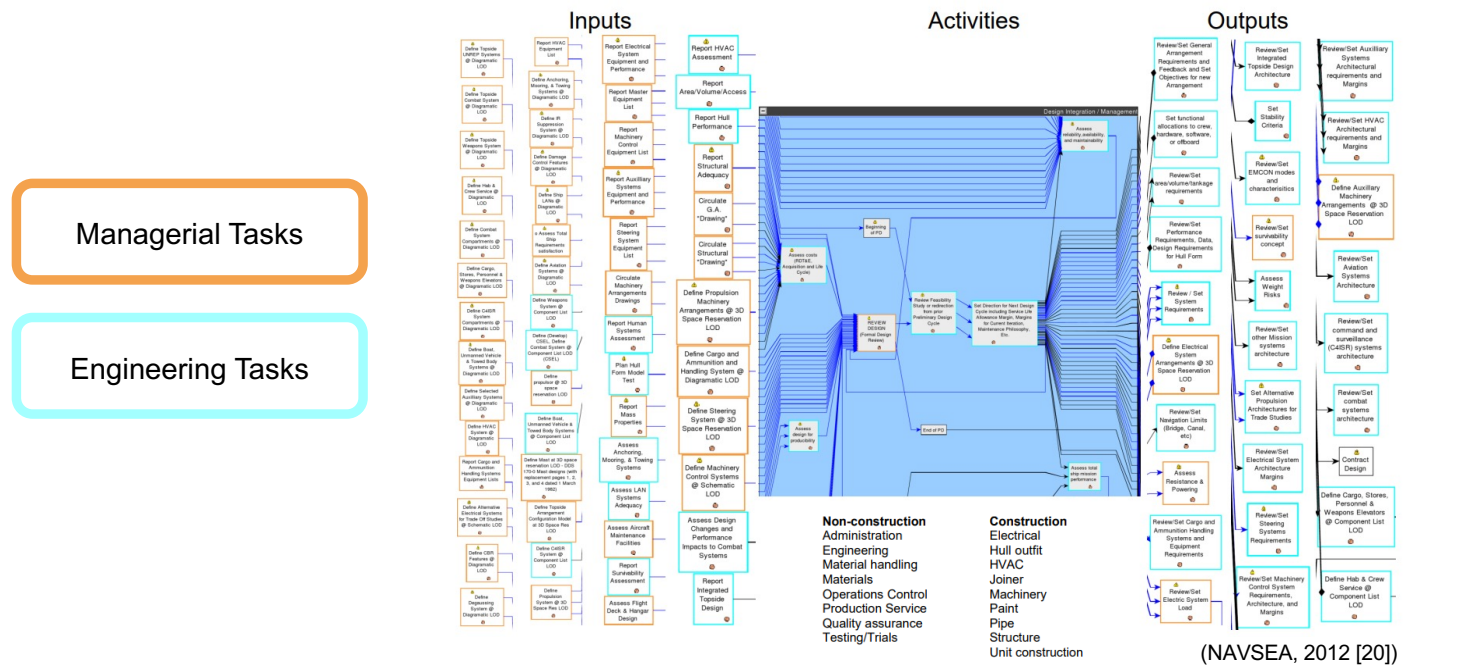


For example, passenger ships in the UK will require the following certification:

- Passenger Ship Safety Certificate
- International or Domestic Safety Management Certificate
- MCA approval for manning
- MCA approval for passenger counting and recording
- if over 24m but under 400GT a Declaration on Anti-Fouling Systems
- International Anti-Fouling Certificate (instead of a Declaration) if 400GT or over
- if carrying Dangerous Goods and built after 1 September 1984, a Document of Compliance for the Carriage of Dangerous Goods
- if over 1000 GT, a Certificate of Insurance or Other Financial Security in Respect of Civil Liability for Bunker Oil Pollution Damage

(Maritime and Coastguard Agency, 2023 [28])

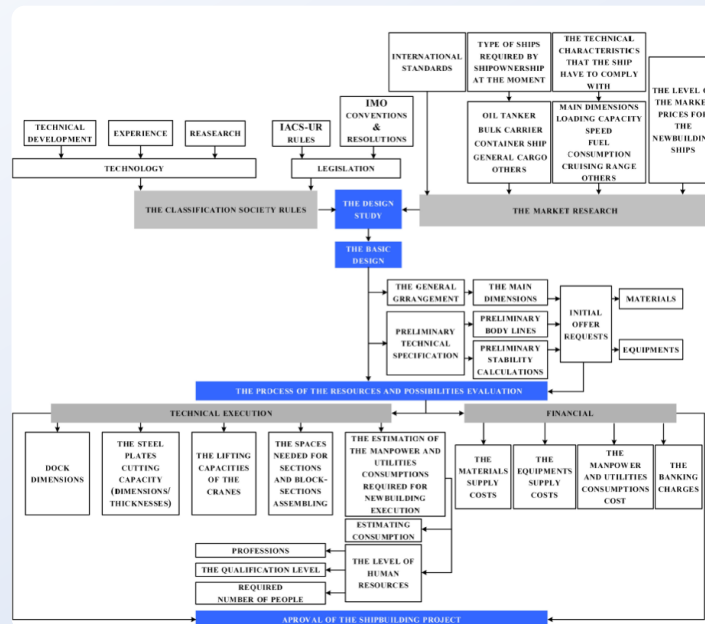
Complexity in detail design is a mix between technical complexity and the complications of managerial coordination.



(NAVSEA, 2012 [20])

## Detailed Design – Sample Process Execution

### Design Stages at Constanta Shipyard



NOTE: These process maps are interpretations of the ship design (detailed engineering phase) logic and may vary from company to company.

(Manea & Manea, 2023 [25])

### A team in the Detailed Design Stage sees:

**Ship in discrete functional parts and systems that must be assessed for client and regulatory compliance, technical feasibility, and compatibility with other functional parts.**

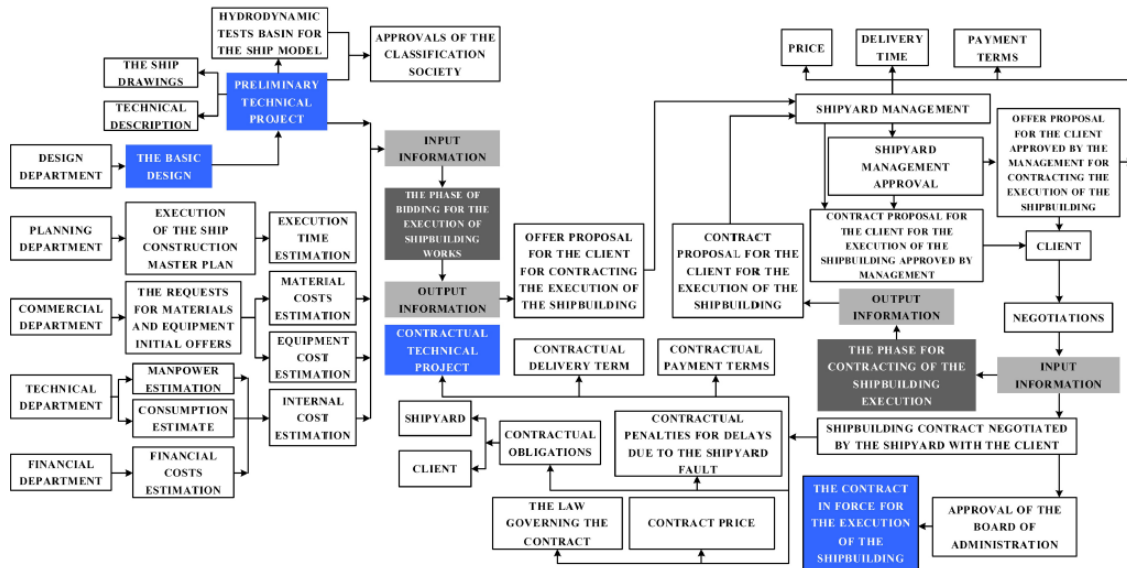
**Main Goal of ship designers:** Correctly define and evaluate functional parts or systems using existing tools (focus on individual specialized tasks)

**Main Goal of ship and systems managers:** Ensure proper coordination (with internal and external parties) to meet project deadlines and support the facilitation of functional parts and systems integration.

#### Information:

- Data is increasingly becoming available. Quantity of information balloons tremendously and the coordination of meta-data and revision information becomes critical
- Data integration becomes harder as format types and the number of team members increase drastically
- Inherent data quality becomes relevant, so data checking and quality control need to happen simultaneously or after data is generated

When a ship design is ready for execution, intermediary steps related to ship design contracting follows.

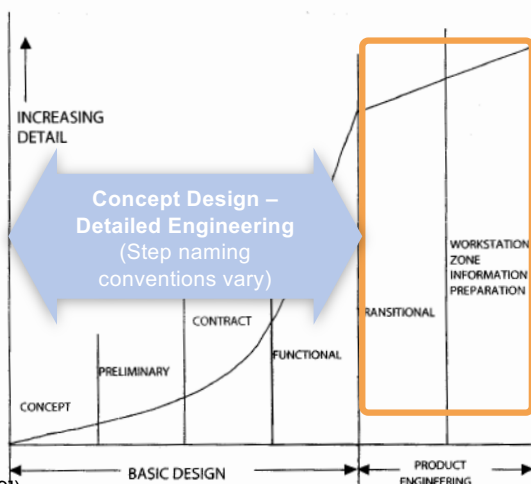


NOTE: These process maps are interpretations of the ship design (contract phase) logic and may vary from company to company.

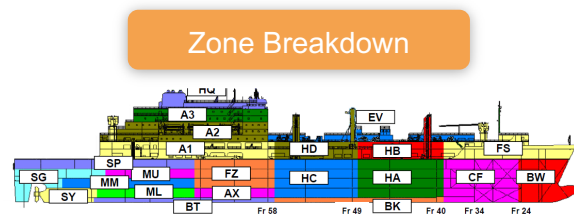
(Manea & Manea, 2023 [25])

When a contract is won, the ship design and design outputs are converted so they are production-ready. This phase is often called 'transitional design' which involves the conversion of the functional ship outputs into Block and or Zone orientation based on the facilities available in the yard. The ship virtual prototype is also often ready for the development of production drawings.

Zones are developed for ease of construction. These are areas of sea-frame that are in physical proximity, and that serve similar or bundled functions and services. Some yards will use the term superblock or block assemblies instead of zones.



(Gale, 2003 [29])



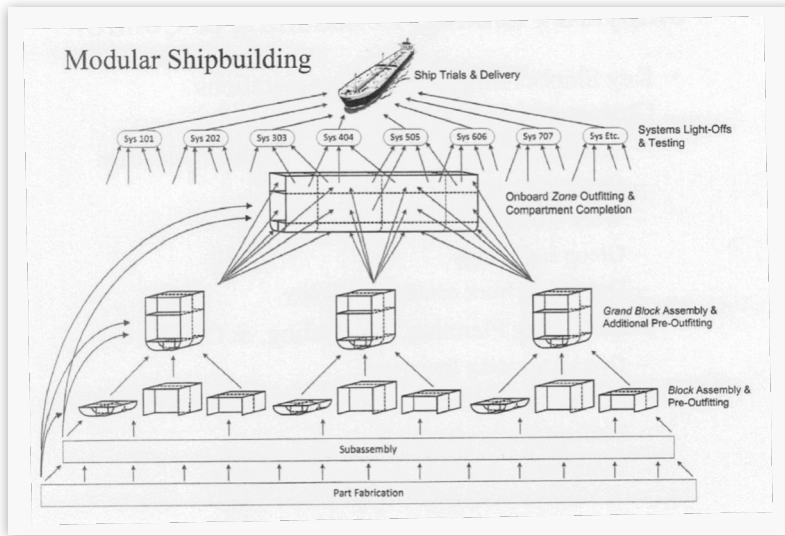
| Type  | Zone | Description                   | Type  | Zone | Description             |
|-------|------|-------------------------------|-------|------|-------------------------|
| Cargo | BK   | Bilge Keel & Double Bottom    | Mach  | SG   | Steering Gear           |
| Cargo | HA   | Multipurpose Hold #1          | Cargo | FZ   | Freeze/Chill            |
| Cargo | HC   | Multipurpose Hold #2          | Cargo | CF   | Cargo Fuel Tanks        |
| Mach  | AX   | Auxiliary Machinery Room      | Accom | A3   | Accommodations Upper    |
| Accom | A1   | Accommodations Lower          | Cargo | FS   | Foc'sle                 |
| Mach  | BT   | Machinery Bilge & Waste Tanks | Cargo | HD   | Topsides Hold 2         |
| Mach  | MU   | Machinery Upper               | Cargo | BW   | Bow                     |
| Mach  | ML   | Machinery Lower               | Cargo | HB   | Topsides Hold 1         |
| Mach  | MM   | Machinery Mid                 | Cargo | SP   | Specialty Cargo         |
| Mach  | SY   | Shaft Alley                   | Accom | HQ   | Bridge & Communications |
| Accom | A2   | Accommodations Mid            | Cargo | EV   | Elevator Houses         |

22 Total Zones { 7- Machinery, 11- Cargo, 4- Accom } - 3 IPT Areas

(Pal, 2015 [24])

Source: T-AKE program, Spring 2005

**Block Assemblies, Super Blocks and or Zones are made up of systems, steel blocks, and their respective sub-divisions (e.g., a structural block or outfit unit, a subassembly of either, and ultimately, a part or component).**



Steel Parts



Steel Assemblies



Steel Blocks

(Koenig, 2019 [30])

**NOTE: Not to be confused with the actual shipbuilding process. Arrows indicate one way for ships to be decomposed in modular shipbuilding.**

**To facilitate construction, work is organized according to Group-technology based process lanes.**

Shopfloor work is grouped in terms of production characteristics and processes. Cellular work centers or process lanes become easier to establish, consolidating equipment and workers with similar skills. Task packages are therefore reorganized or developed from zone-based data to suit finer divisions of labor.



Cutting



Welding

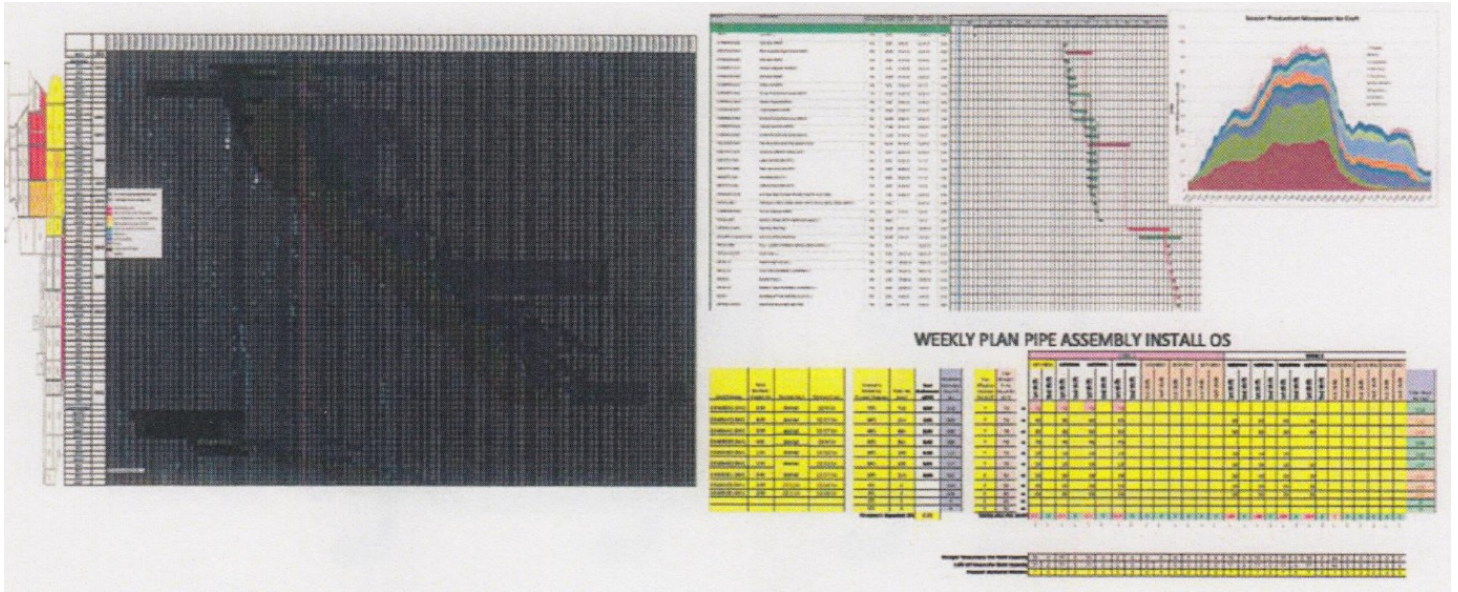


Steel transport & assembly

(Song & Zhou, 2021 [31])

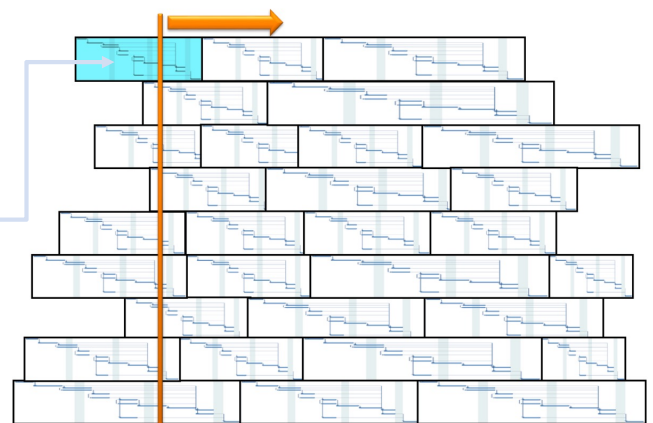
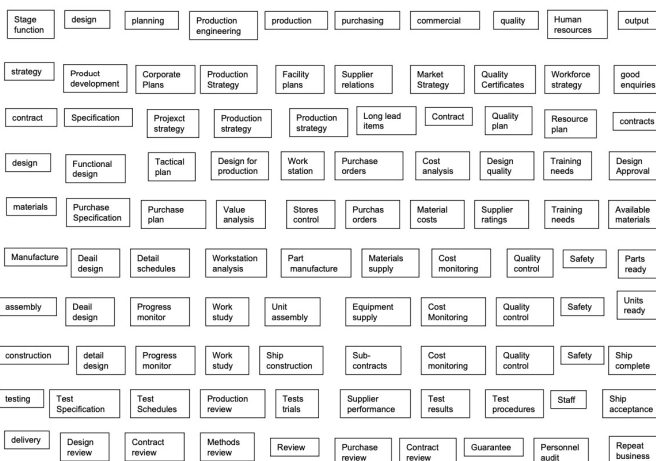
**NOTE: This diagram may vary from company to company.**

Work and task description documents can increase substantially during the production phase, to incorporate all the technicians in the shop floor. Demand and work content variability become tricky to coordinate.



(Koenig, 2019 [30])

For shipyards that have multiple projects, this degree of scheduling inflates rapidly. A high understanding of utilization and workload leveling, advanced planning, and communication are key.



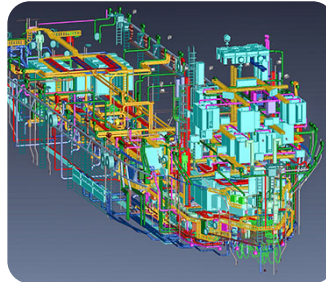
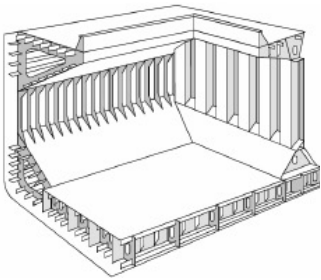
Bruce's 10x10 Activity Map for Ship design and Shipbuilding

Simultaneous Scheduling

(Bruce, G., 2021 [32])

(Sollid, F. 2016 [33])

In Ship Construction, the ship is mainly viewed as a combination of structure and outfit.



(Bonnin-Pascual, et al., 2012 [83])

### Structure (Hullform + Superstructure)

Hull Shell Plating, Decks, Stiffeners, Rudders, Castings, etc.

Hierarchical, flow-oriented



### Outfitting

Piping & hull attachment fittings, furnishings, cargo handling gear, cargo piping, electrical generation and distribution, main propulsion machinery, etc.

Heterogenous, Not very flow-oriented



Triple-E Maersk Block  
[atlasofplaces.com/photography/maersk-triple-e/](http://atlasofplaces.com/photography/maersk-triple-e/)

Due to the heterogeneity of outfitting parts, outfitting work is often completed at different times leading to various outfitting phases during construction.

On-block Outfitting



Machinery and generators (covered in wood boxes) are already outfitting on the steel or structural block.

Better working conditions and access, with downsides in weight for assembly

On-board Outfitting (Dock or Quay Outfitting)



Engine installed after ship blocks have been assembled.

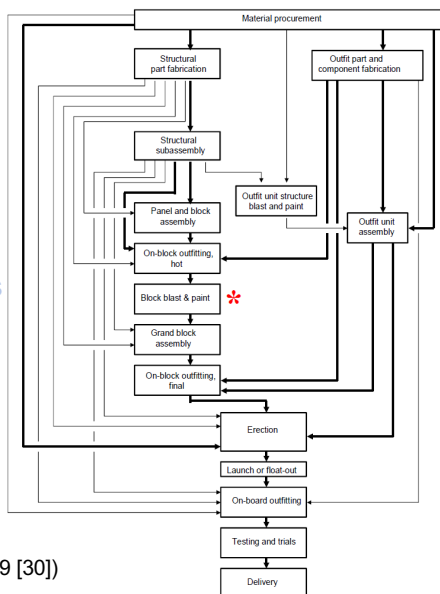
Delay in installation allows for concurrent design and production, but much more costly to install

Figures from (Sanchez, 2018 [84])

The ship construction process becomes highly focused on flow and the coordination of materials, parts, and labor.

The focus question is: How can we incorporate more hierarchical practices to make material flow, labor coordination and planning more efficient and less costly? Economies of scale (EoS) are critical to consider.

Ship Building Materials Flow



(Koenig, 2019 [30])

Example: How to best manage the construction of a Suez Max Tanker?

Tanker ~150.000 dwt

- Hull steel for tanker vessels is approximately **20.000 tons of steel per vessel**
- If the yard delivers 20 Suez tankers, it will need to process: **400000 tons of steel**
- Large vessels will have approximately **3.000-4.000 pipes**

**Well over 1 million parts to coordinate**

| Category                       | Shipbuilding            | Aviation         | Automobile                    |
|--------------------------------|-------------------------|------------------|-------------------------------|
| Number of Parts (Ten Thousand) | 250-1000                | 15-150           | 0.3-1                         |
| Manufacturing Method           | Engineer to order (ETO) | Order production | Order production and assembly |

## Shipyards need to understand how EoS affects their business and how they can strategically keep costs low by increasing volume or scale.

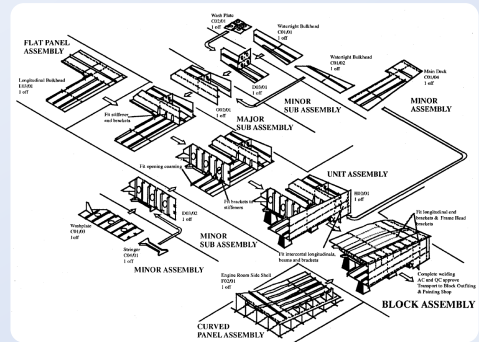
Based on EoS, it is smarter to spread capital and non-manufacturing costs and focus on specialized labor and capital. These strategies are reflected in the shipyard design of a shipbuilding company.



Shipyards, South Korea (Daewoo)

### Example: Integrated Yard

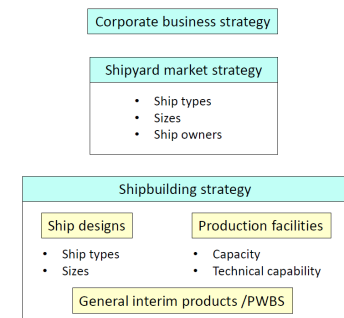
If a shipyard thinks it can handle the costs of steel fabrication, systems integration, and assembly – it will have a more integrated yard with a steel stockyard and steel fabrication workshops.



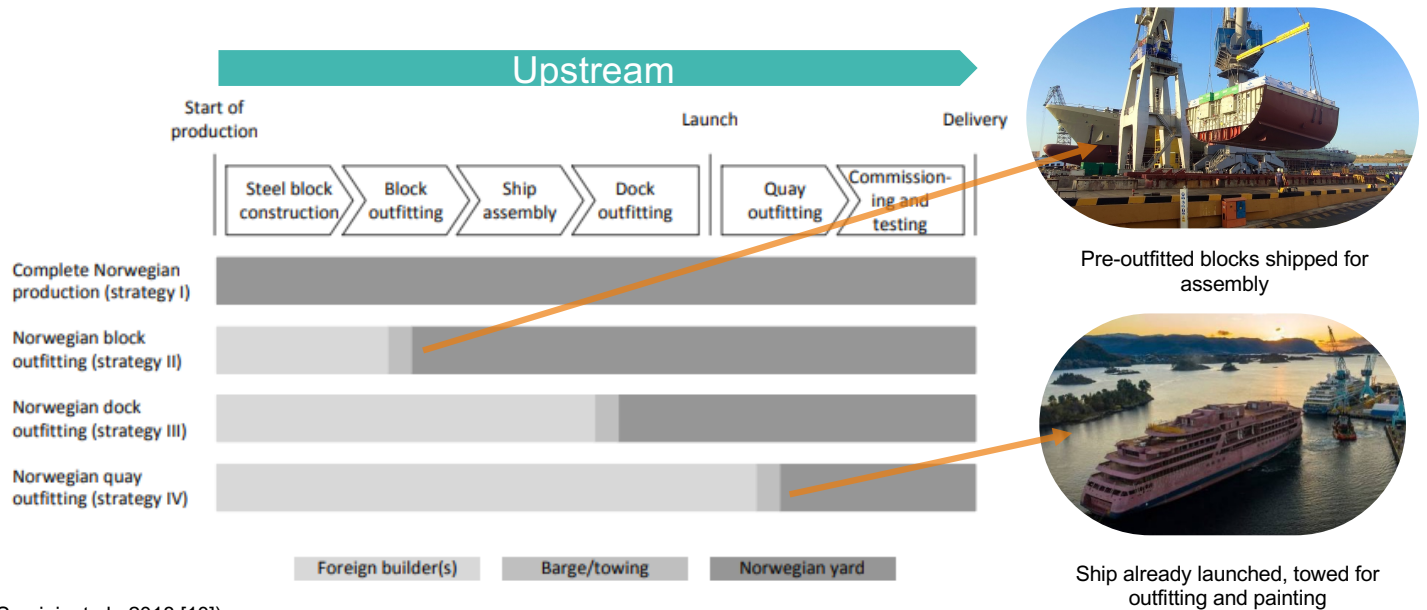
## As of late it is much more expensive to build the hull in Europe due to high labor costs and throughput costs. For example, in 2013, European yards had a lower productivity average compared to shipyards in Japan and Korean.

These business & production factors have a heavy influence on the shipbuilding and build strategy. The build strategy is a plan for design, materials management, production, and testing in the shipyard.

| SHIPBUILDING DESIGN METRICS                          |        |         |        |        |         |        |        |         |        |        |         |        |                 |
|--|--------|---------|--------|--------|---------|--------|--------|---------|--------|--------|---------|--------|-----------------|
| METRIC   | JAPAN  |         |        | KOREA  |         |        | CHINA  |         |        | EUROPE |         |        | OVERALL AVERAGE |
|  | LOW    | AVERAGE | HIGH   | LOW    | AVERAGE | HIGH   | LOW    | AVERAGE | HIGH   | LOW    | AVERAGE | HIGH   |                 |
| Technology Level (Best Practice Level)               | 4.1    | 4.45    | 4.7    | 4.2    | 4.5     | 4.7    | 3.6    | 3.8     | 4      | 4.3    | 4.6     | 4.8    | 4.34            |
| Productivity - CGT/Employee Year Incl. SC            | 173    | 201     | 211    | 57     | 82      | 89     | 13     | 22      | 29     | 31     | 43      | 140    | 82              |
| Performance - Man Hours/CGT Incl. SC                 | 11.6   | 9.47    | 9.5    | 34.9   | 23.03   | 22.5   | 156.7  | 88.1    | 68.8   | 63.9   | 44.29   | 14.3   | 64              |
| Steel Tonnes/Worker Year Incl. SC                    | 128    | 185     | 268    | 17     | 68      | 91     | 17     | 26      | 32     | 20     | 23      | 55     | 75              |
| Steel Tonnes/Steel shop Area                         | 1.66   | 2.34    | 2.76   | 1.9    | 2.43    | 2.98   |        | 1.01    |        | 0.49   | 0.5     | 0.52   | 1.57            |
| Steel Shop Area/Total Shipyards Area                 | 0.095  | 0.104   | 0.199  | 0.067  | 0.137   | 0.199  |        |         | 0.252  | 0.192  | 0.266   | 0.384  | 0.152           |
| CGT/Shipyards Total Area                             | 0.26   | 0.44    | 0.77   | 0.39   | 0.68    | 1.25   | 0.36   | 0.45    | 0.5    | 0.28   | 0.36    | 0.78   | 0.43            |
| Production Workers Incl. SC/Total Employees Incl. SC | 0.83   | 0.81    | 0.78   | 0.9    | 0.83    | 0.83   | 0.9    | 0.92    | 0.68   | 0.7    | 0.69    | 0.68   | 0.85            |
| Total Employees Incl. SC/Total Area                  | 0.0012 | 0.0015  | 0.0045 | 0.0044 | 0.0059  | 0.0145 | 0.0172 | 0.014   | 0.0279 | 0.0048 | 0.0083  | 0.0098 | 0.0070          |
| Annual CGT/Total Shop Area                           | 3.1    | 4.27    | 6      | 3.26   | 4.95    | 8.54   |        | 1.41    |        | 1.12   | 1.34    | 2.04   | 2.99            |
| Annual CGT/building Berth Area                       | 3.2    | 5.5     | 10.4   | 12.5   | 14.3    | 17.5   | 6.3    | 9       | 10.9   | 7.4    | 10.2    | 13.8   | 8.70            |

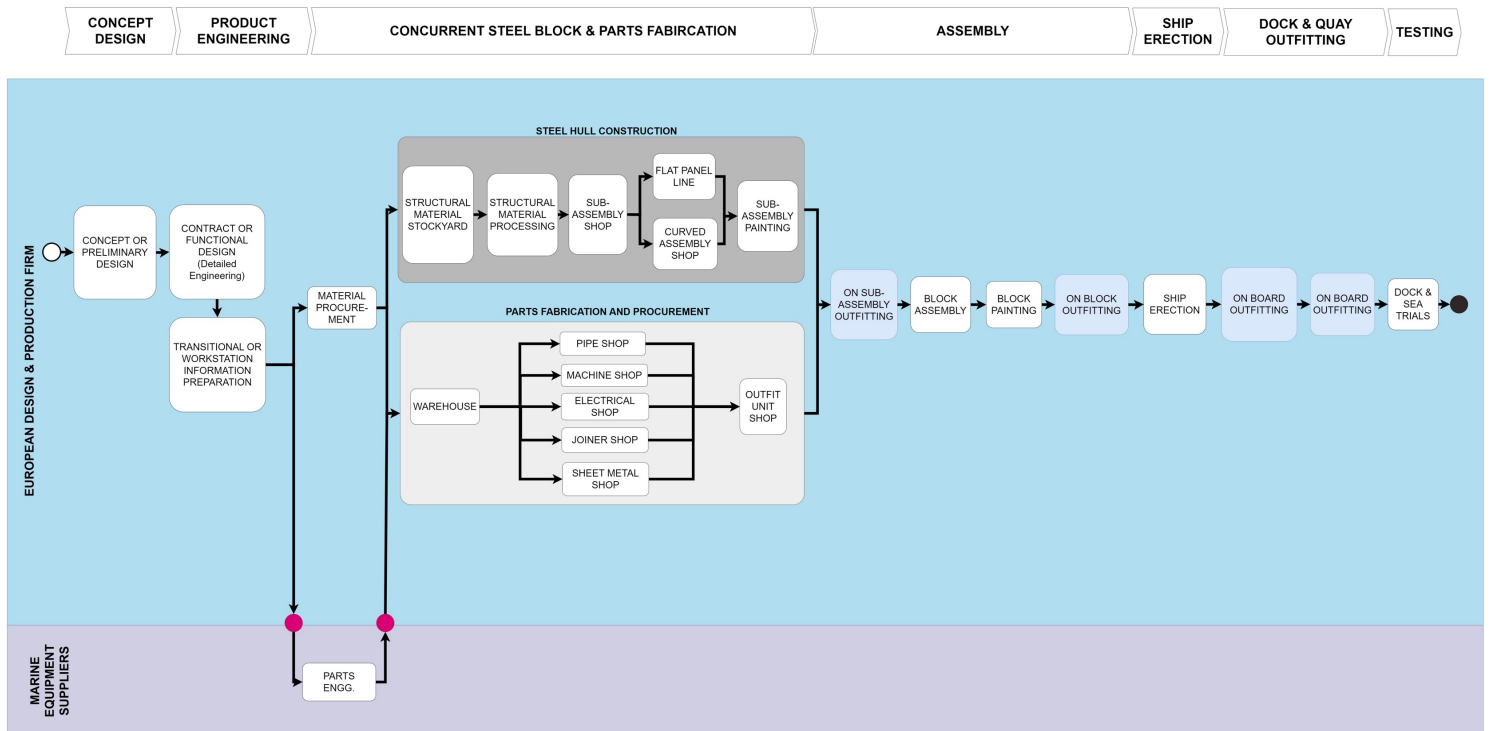


Semini et al. conducted studies on the different strategies employed in Europe, particularly in Norway. They found that although there are still some shipyards that fully construct a ship locally, the most common strategies include offshoring the entire hull construction and or blocks abroad.

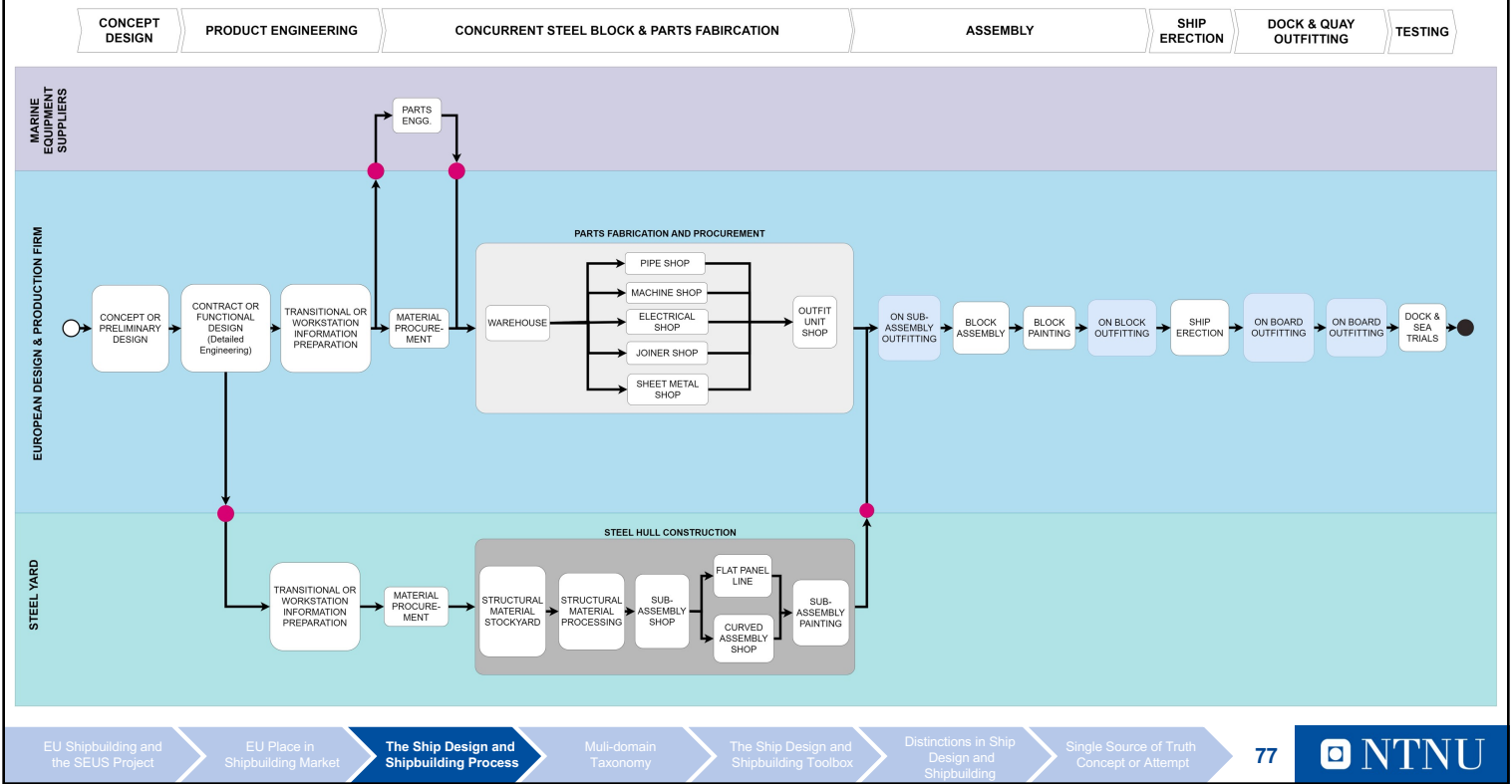


(Semini, et al., 2018 [10])

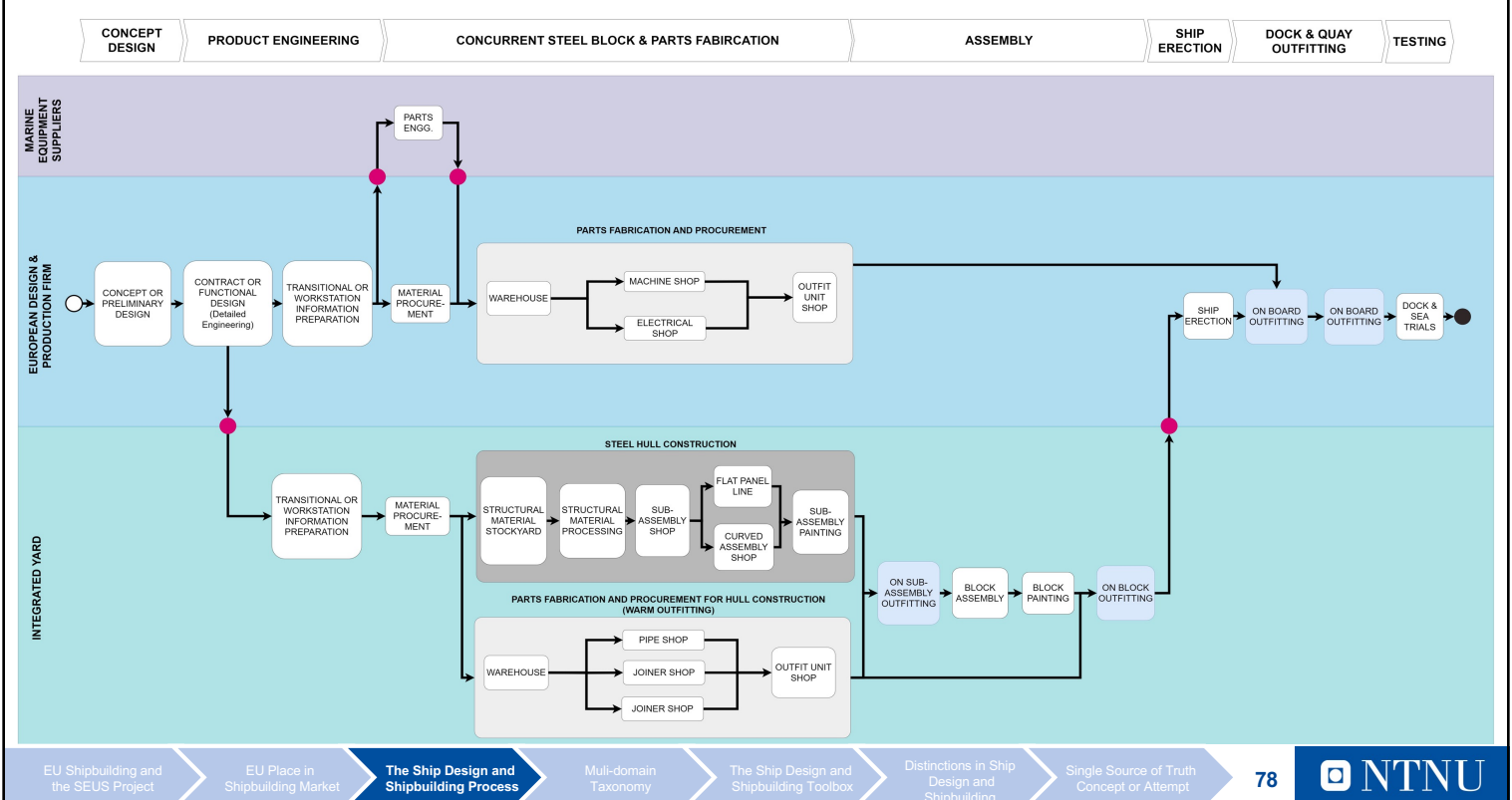
### STRATEGY I - Complete Norwegian Production



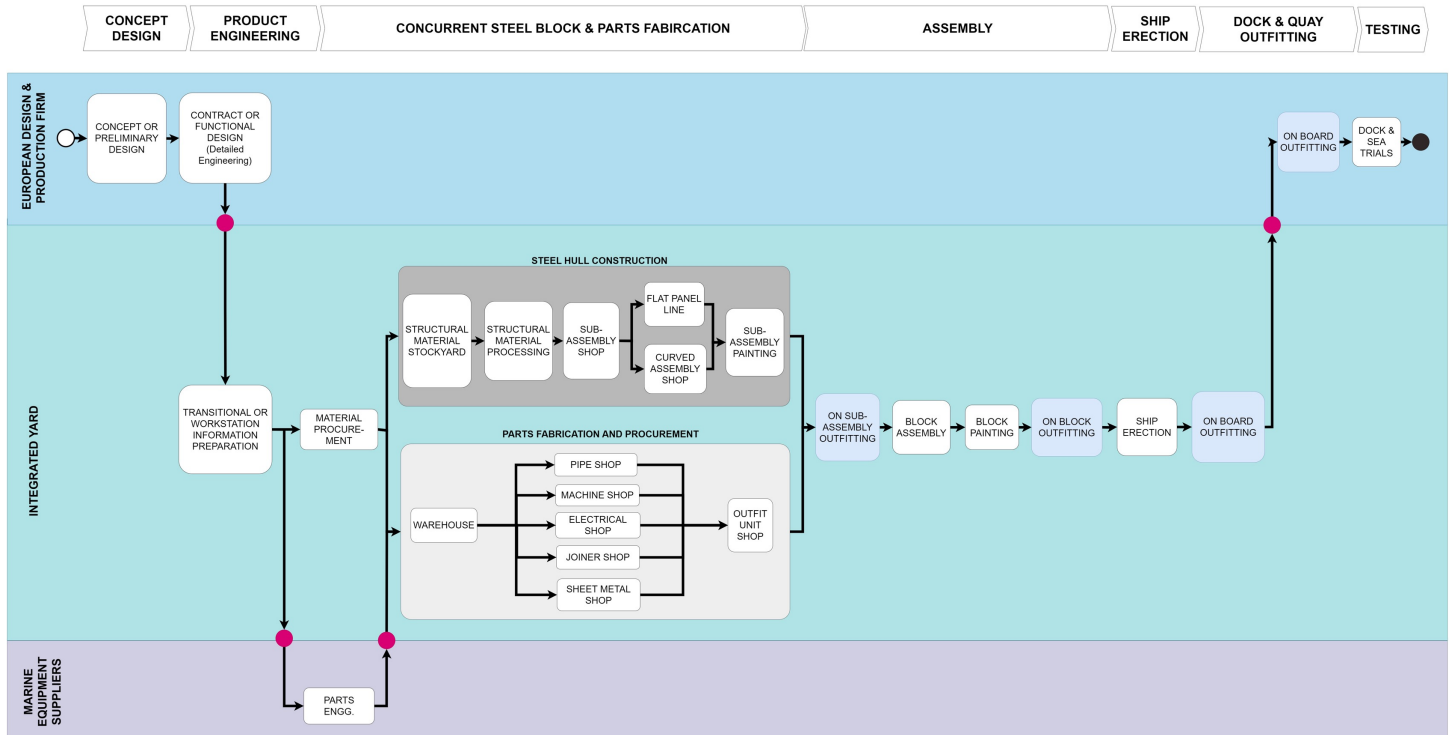
## STRATEGY II - Block Outfitting and Assembly in a Norwegian Yard (Hull Construction Abroad)



## STRATEGY III - Dock Outfitting in a Norwegian Yard (Pre-outfitting)

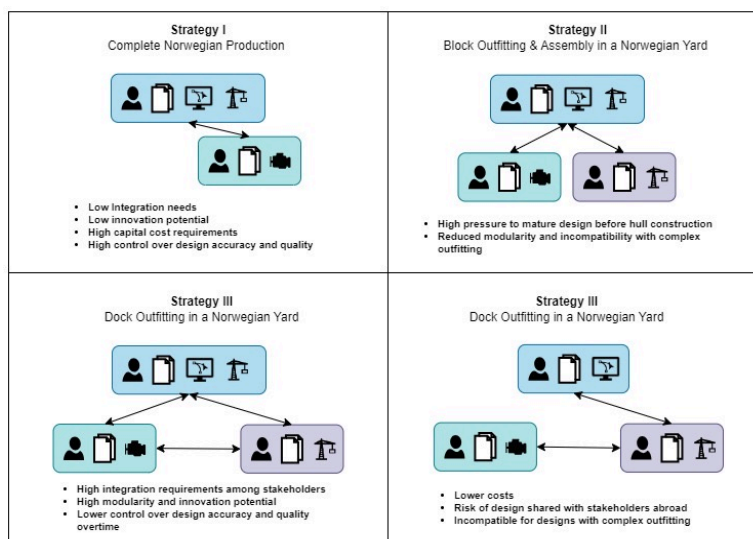


# STRATEGY IV - Quay Outfitting



Each strategy faces its own risk, both in data and systems integration, due to the variability in the stakeholders, interactions, and information exchange.

Every yard will have unique facets of their production, aligning and deviating from these four strategies.



Integration Risks for Different Strategies

When the vessel is launched and on-board outfitting is complete, testing and sea trials are performed to ensure that the vessel can float and is operational as expected.

Launching



Side and Slipway Launching

Commissioning



Ship Ceremonial Christening and Commissioning

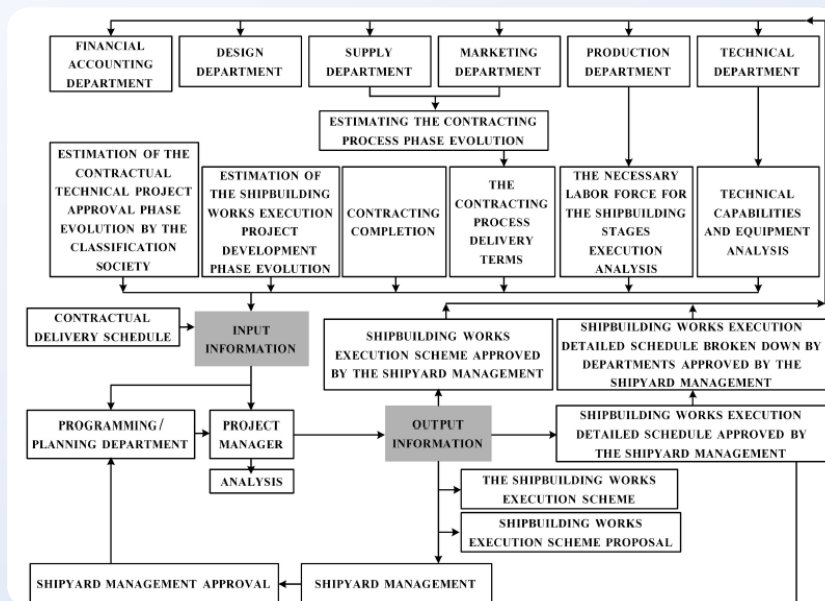
Testing and Delivery



Turning Tests and Bollard Pull Testing

Construction – Sample Process Execution  
Shipbuilding Stages at Constanta Shipyard

Pre-acceptance of the Construction Plan

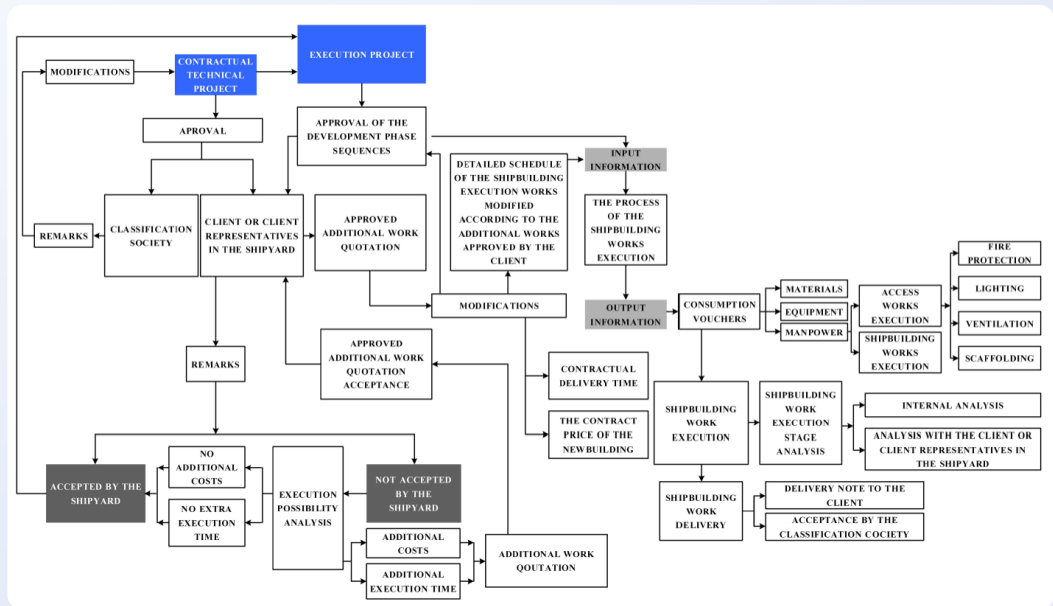


NOTE: These process maps are interpretations of the ship design (ship construction) logic and may vary from company to company.

(Manea & Manea, 2023 [25])

## Construction – Sample Process Execution Shipbuilding Stages at Constanta Shipyard

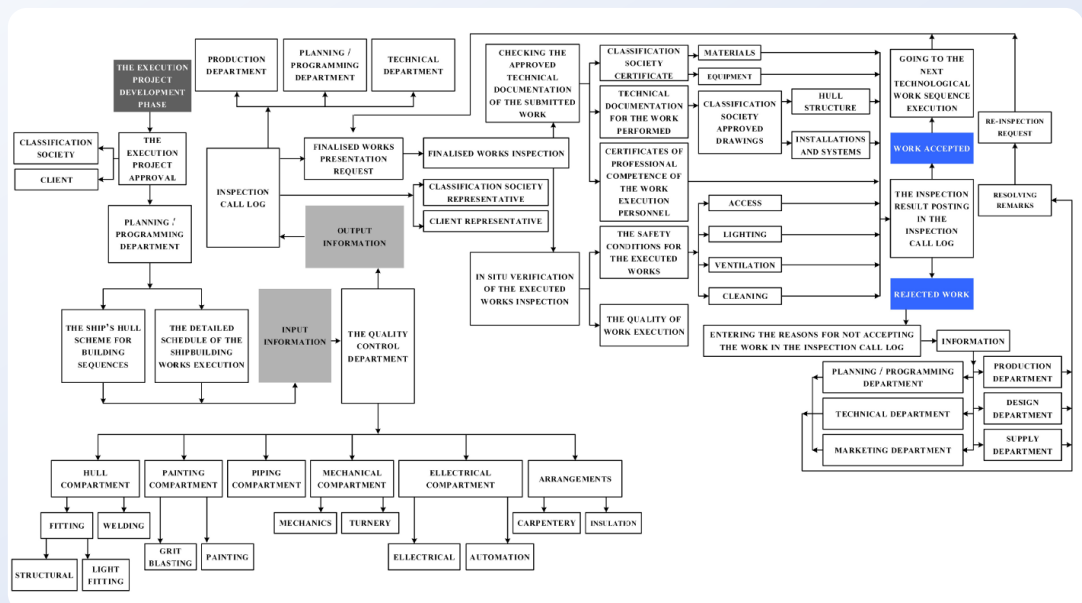
### Work Execution



NOTE: These process maps are interpretations of the ship design (ship construction) logic and may vary from company to company. (Manea & Manea, 2023 [25])

## Construction – Sample Process Execution Shipbuilding Stages at Constanta Shipyard

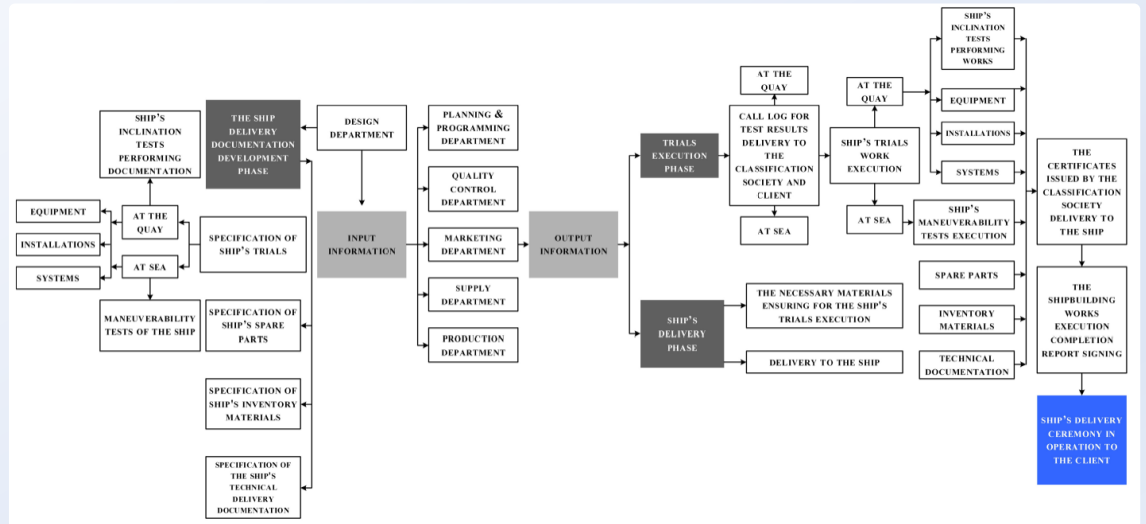
### Quality Assurance



NOTE: These process maps are interpretations of the ship design (ship construction) logic and may vary from company to company. (Manea & Manea, 2023 [25])

## Construction – Sample Process Execution Shipbuilding Stages at Constanta Shipyard

### Sea Trials and Testing



NOTE: These process maps are interpretations of the ship design (ship construction) logic and may vary from company to company. (Manea & Manea, 2023 [25])

### A team in the Construction Stage sees:

**Ship as STRUCTURE + OUTFIT, focusing on the hierarchical construction and assembly of physical ship parts and blocks.**

**Main Goal of ship designers:** Develop a virtual prototype that can be used for reorientation of ship definition into ship blocks and work packages in the shopfloor. Refine ship definition.

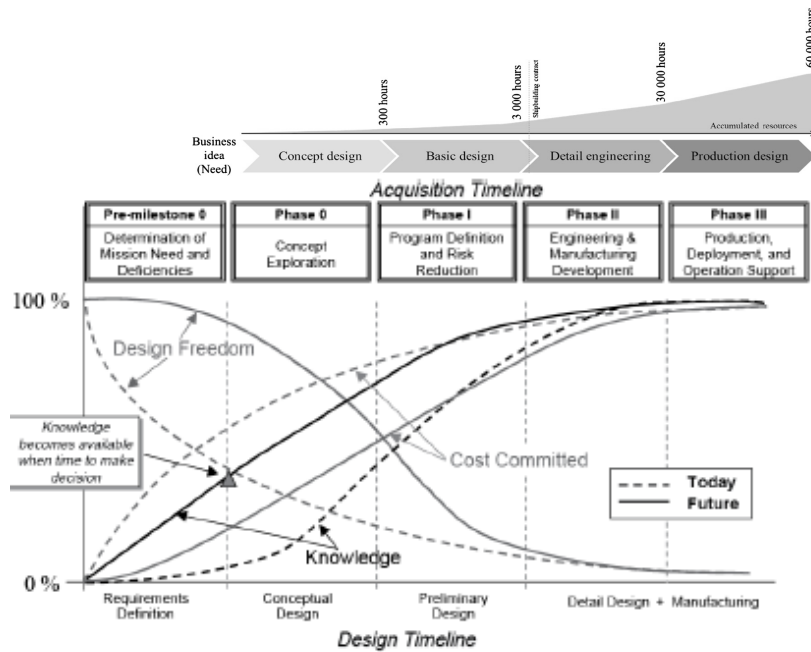
**Main Goal of planners:** Ensure proper and efficient coordination of parts and materials (with external suppliers and stockyards), proper planning of technicians and staff on the shop floor, and continual liaising with the design team.

**Main Goal of finance and business team:** Develop strategic plans for sustained competitiveness and ensure availability of resources and facilities that align with business strategies.

#### Information:

- Information on ship design becomes more and more detached from functional representations
- Work information balloons from ship data to construction information (mainly broken down in action or tasks)
- Information from multiple suppliers and yards need to be integrated
- Information from checking and tests generated

**Costs are most heavily influenced at the early stages of the design, when less knowledge is available. Risks are gradually reduced but errors become extremely expensive to correct as the design matures.**



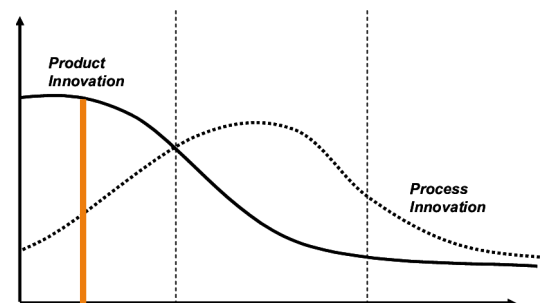
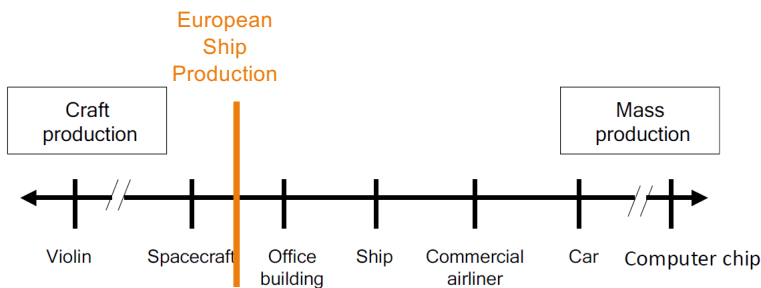
(Shields, 2017 [85])

**Recall that in the production spectrum, ships fall between craft and mass production.**

In the Production vs Innovation curve where there is always a trade-off between production efficiency and product innovation. European shipbuilding therefore faces more challenges to tip towards improved process efficiency.

Production Spectrum

Product vs Innovation Curve



(Koenig, 2019 [30])

In addition to the costs in production efficiency, there are additional costs in the form of knowledge leakage. Training and the exchange of tacit knowledge will be critical to circumvent these effects.

The learning curve effect is a phenomenon where the unit cost of production decreases in a predictable pattern as the number of units produced doubles. **This is due to improvements in worker and management learning, tooling, production processes, and engineering changes.**

NASA estimates about **85% learning curve effect for the shipbuilding industry** which is equivalent to aerospace with about 80 to 85% learning curve effects. This means that SD&SB is very sensitive to learning curve effects.

| Example  | Improving Parameter  | Cumulative Parameter                | Learning Curve Slope, percent | Time Frame  | Number of Volume Doublings |
|--|--|-------------------------------------|-------------------------------|-------------|----------------------------|
| 1. Model-T Ford production                         | Price  | Units produced                      | 86                            | 1910-1926   | 10                         |
| 2. Aircraft assembly                               | Direct man-hours per unit                                  | Units produced                      | 80                            | 1925-1957   | 3                          |
| 3. Catalytic cracking units for petroleum          | Days required per 100 million barrels                      | Million barrels run                 | 90                            | 1946-1958   | 10                         |
| 4. Cost of fluid cracking units                    | Cost per barrel of capacity                                | Installed design capacity of plants | 94<br>80*                     | 1942-1958   | 5                          |
| 5. Equipment maintenance in general electric plant | Average time to replace a group of parts during a shutdown | Number of replacements              | 76                            | Around 1957 | 4                          |

(Cunningham, 1980)

## Ship Design and Shipbuilding Process: Section Summary

Each phase in the upstream value chain sees the ship differently. As such, the reorientation of ship data is common.

- **Concept Design:** Ship AS Complex System of Systems (SoS) with plenty of converging and conflicting design requirements.
- **Detailed Engineering:** Ship in discrete functional parts and systems that must be assessed for client and regulatory compliance, technical feasibility, and compatibility with other functional parts.
- **Construction:** Ship as STRUCTURE + OUTFIT, focusing on the hierarchical construction and assembly of physical ship parts and blocks.

Data serves multiple purposes across the entire upstream value chain:

- For decision-making and planning
- For communication as different teams are spread out to handle complexity
- To circumvent learning curve effects
- To integrate disparate stakeholders that can also lead to information ownership issues
- To help de-risk innovation

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## Best Practices on Ship Design and Shipbuilding: Outline

1. EU Shipbuilding and the SEUS Project
2. EU Place in Shipbuilding Market
3. The Ship Design and Shipbuilding Process
- 4. Multi-domain Taxonomy**
5. The Ship Design and Shipbuilding Toolbox
6. Distinctions in Ship Design and Shipbuilding
7. Single Source of Truth Concept or Attempt

**There are a few key features in ship design and shipbuilding that affect the information systems that are used in design firms and yards, as noted in the previous section.**

Unfortunately, these features have not changed drastically since the 1990s. The reliance on legacy tools increases the risks of incurring high technical debt in ship design software.

**Key Features:**

1. Information and data management priorities vary in every stage of the lifecycle
2. Functional Breakdown structures are common in design while Physical Block and Zone Breakdown structures are common in construction
3. Challenging exchange and retention of information across each phase
4. Rapid increase in data generation from design definition, evaluation, and testing

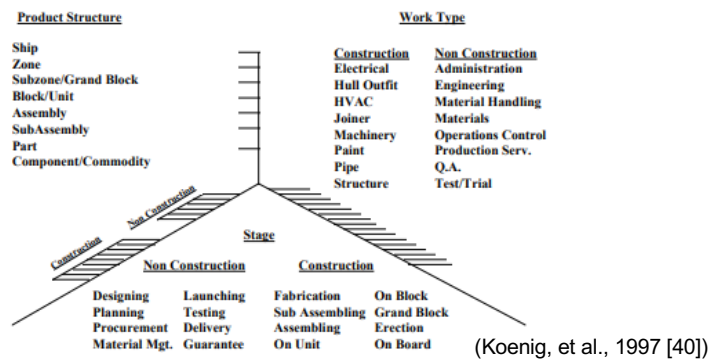
| Business function  | Mid-1960s      | Mid-1990s                       |
|--------------------|----------------|---------------------------------|
| Ship specification | System         | System                          |
| Ship design        | System         | Varies with zone, system, other |
| Cost estimation    | System         | Varies                          |
| Budgeting          | System         | Product and process             |
| Planning           | System         | Product and process             |
| Operations         | System / trade | Varies with trade, area, skill  |

(Koenig, et al., 1997 [40])  
Design and Build Orientation from 1960s to 1990s

**Decomposition of work as a basis for planning: The definition of a standard ‘work element’ has always been a challenge in ship design. Historically, the work element is based on functional breakdowns, but this has led to constraints in incorporating scheduling and planning data.**

As echoed by NAVSEA [20] and by Pal (2015) [24], breaking down a ship by functions greatly limits the incorporation of planning data, BOM, BOP, and connection with the data format.

- (Group) 100 - Hull Structure
- (Element) 101 - General Arrangement-Structural Drawings
- (Subgroup) 110 - Shell and Supporting Structure
- (Element) 111 - Shell Plating, Surface Ship and Submarine Pressure Hull
- (Element) 112 - Shell Plating, Submarine Nonpressure Hull
- (Subgroup) 120 - Hull Structural Bulkheads
- (Element) 121 - Longitudinal Structural Bulkheads
- (Element) 122 - Transverse Structural Bulkheads



Functional and Systems Ship Breakdown  
1960s

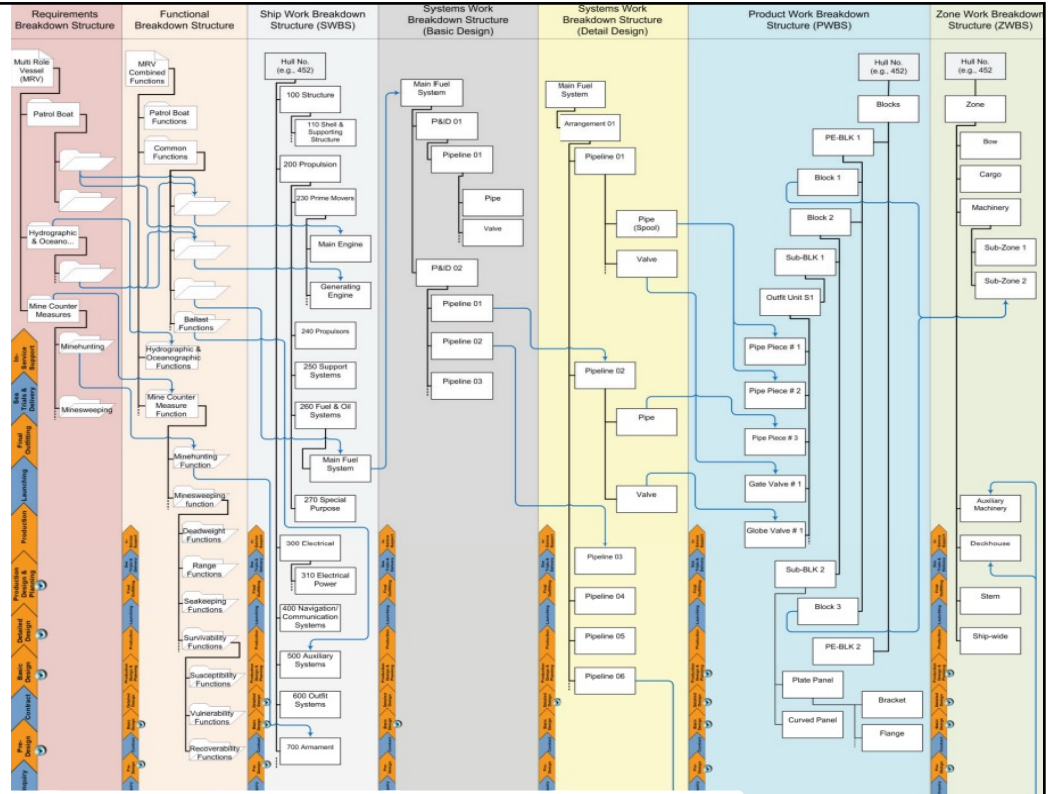
Functional and Systems Ship + Product, Stage, Work Type  
1990s



Despite the incorporation of process, planning, and work type data in PWBS, there is still missing information with the definition of a ship 'Work Element'.

Tedious conversions, revision control, and manual incorporation of 2D/3D files are still the norm today.

(Pal, 2015 [24])

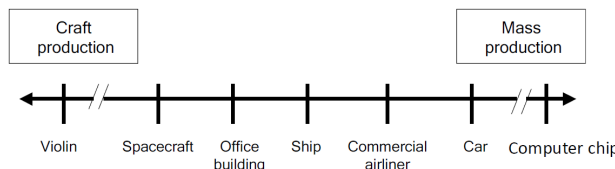


Recall that shipbuilding falls between construction and manufacturing: Construction and manufacturing industries have different 'work element' philosophies. Which philosophy does the ship designer and planner choose?

Approach used in shipbuilding

Construction-oriented industries evolved with a focus on the work to complete the project.

**Task or Activity Focused**



Approach used in Ship Design

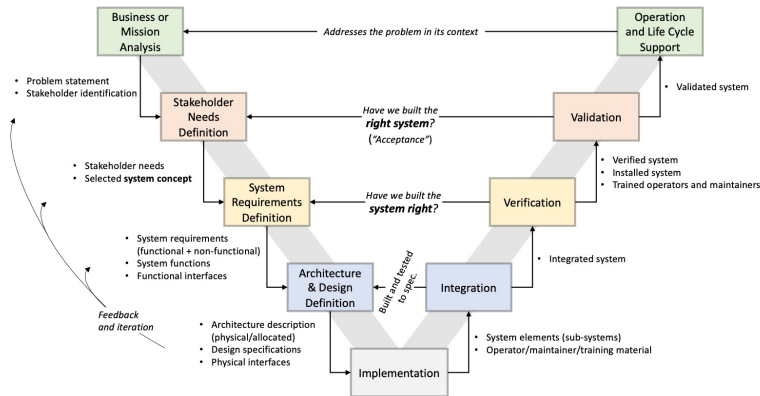
Manufacturing-type industries evolved with a focus on planning units

**Intermediate Product Focused**

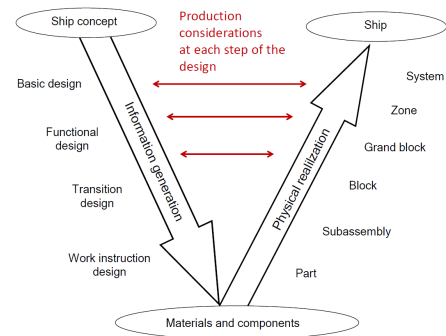
**A common systems engineering approach to the definition of work involves the understanding that these work elements evolve throughout the ship lifecycle.**

The v-model is one way to view the evolution of the work element definition. It incorporates a functional ship concept with physical materials and realization.

**Systems Engineering V-model**



**V-model applied to Ship Design and Shipbuilding**



(Koenig, 2019 [30])

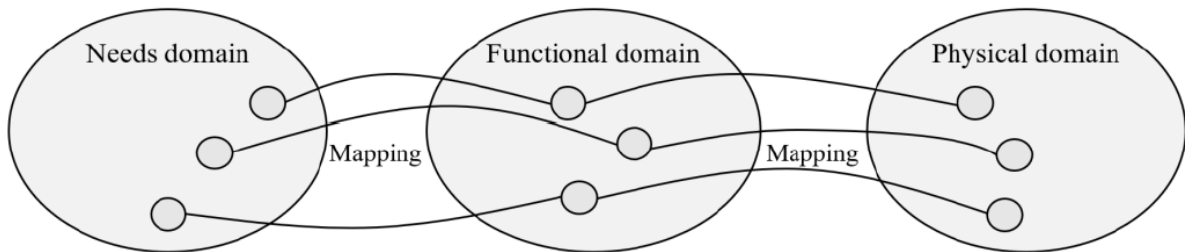
**Unfortunately, this symmetrical assumption of the process is often incomplete and not realistic. Ship design and construction process are not linear and are more stochastic and complex.**

The simplification of the v-model may not apply for a ship due to the following features adapted from Erikstad (1996) [42]. The ship is,

- Highly-integrated structure, operating in the boundary between two fluids
- Multi-dimensional, partly non-monetary performance evaluation
- High cost of error
- Shallow knowledge structure
- Strong domain tradition
- Strict time and resource constraints on the design process
- Predominantly 'one-of-a-kind' and 'engineering-to-order' solutions

An alternative approach to systems design is a process of mapping between design domains (Coyne, Rosenman, Radford, Balachandran, & Gero, 1990 [43]; Pahl & Beitz, 1996 [44]; Suh, 1990 [45]). Pettersen identified three main domains to consider in ship design.

*Synthesis: Find functional specification meeting the needs, and physical description meeting the specification.*



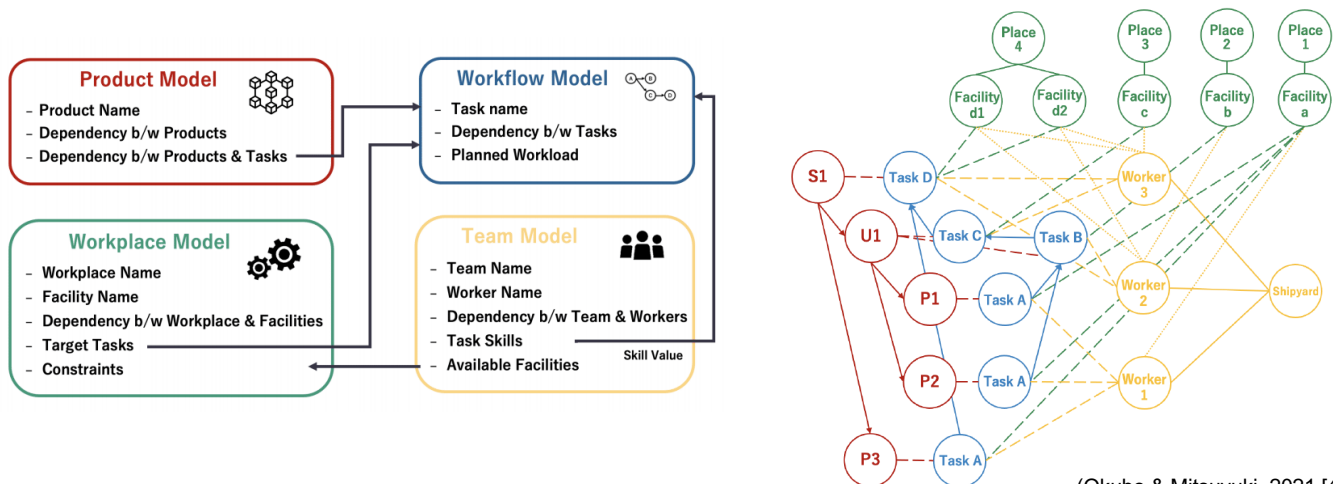
*Analysis: Checking what functions the physical description can produce, and what needs the functions meet.*

(Pettersen, 2018 [50])

Domains - a logical grouping of data, referring to interrelated data about a common purpose, object, or concept.

Outside functional and physical domains, other studies extend to include team, workplace, and workflow data for a more complete virtual prototyping of a shipyard.

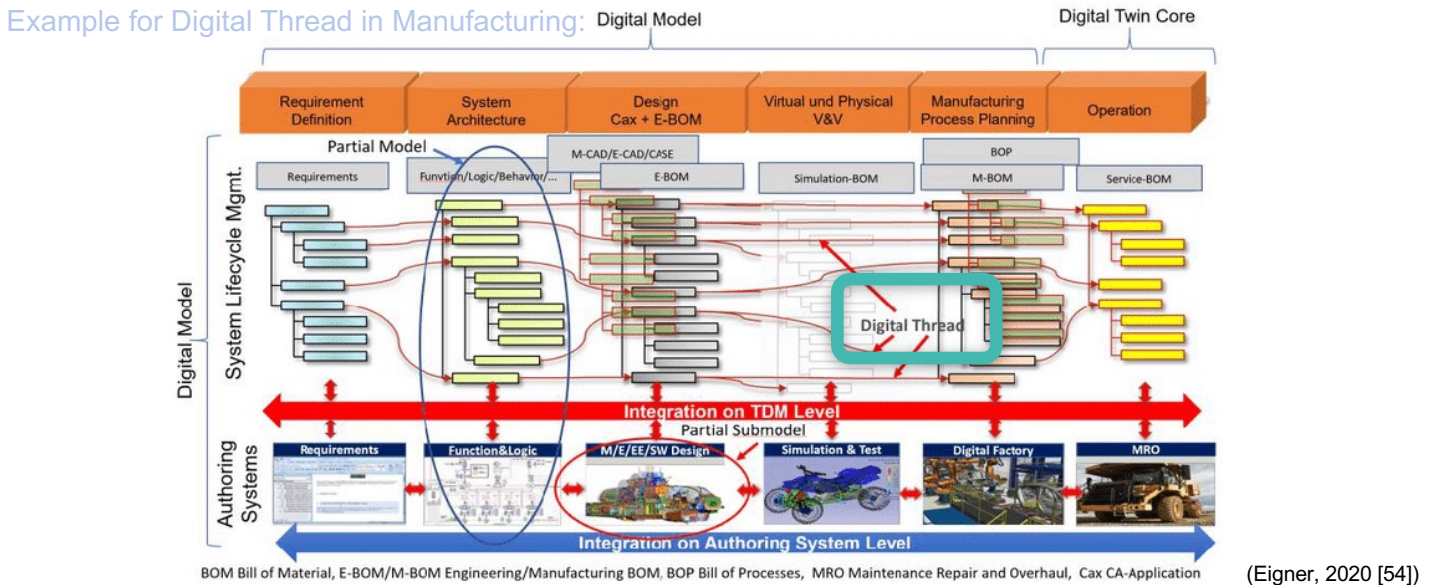
Network Maps are developed in these studies to understand ship data connections between these domains.



(Okubo & Mitsuyuki, 2021 [46])

The incorporation of additional planning data (including workplace, workflow, and people) broadens the concept of a ship digital twin to a more temporal aspect of the entire ship digital thread.

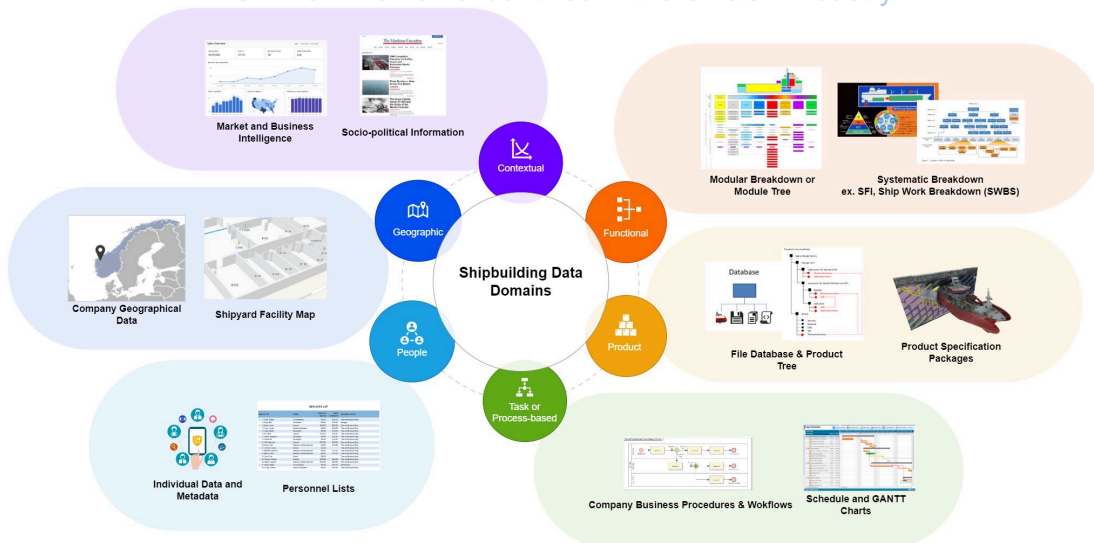
The digital thread enables end-to-end connection with digital models and twins across the entire lifecycle.



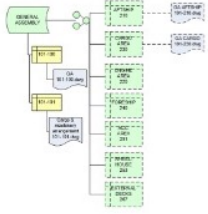
### What types of data are required to enable the integration of information and increase ship design traceability throughout the lifecycle?

Increasing management of various data domains increases overall traceability. These could be in the form of data (structured, unstructured), meta-data, and business ontologies.

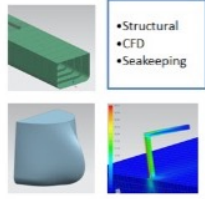
Six Main Domains identified in the SD&SB industry:



## Functional Domain



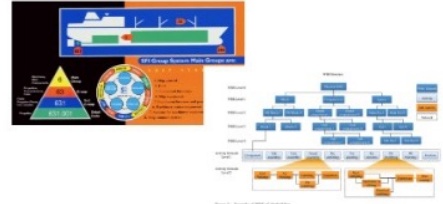
Systems Tree & Library



Functional Analysis



Modular Breakdown or Module Tree

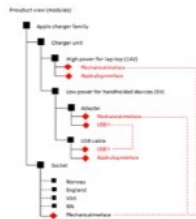


Systematic Breakdown  
ex. SFI, Ship Work Breakdown (SWBS)

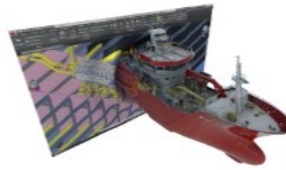
## Product Domain



File Database



Ship Catalogue

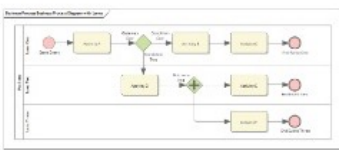


Product Specification Packages

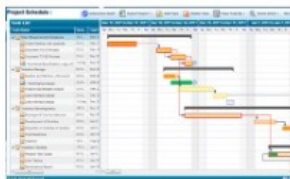
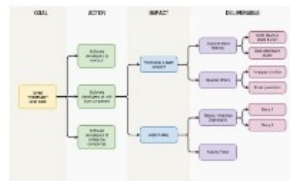


Built Ships

## Task or Process Domain



Company Business Procedures & Workflows



Schedule and GANTT Charts

| Task Name | Start      | End        | Status      |
|-----------|------------|------------|-------------|
| Task 1    | 2023-01-01 | 2023-01-05 | Completed   |
| Task 2    | 2023-01-05 | 2023-01-10 | In Progress |
| Task 3    | 2023-01-10 | 2023-01-15 | Not Started |

Shopfloor Task Packages

## People Domain



Company Network



Individual Data and Metadata

| EMPLOYEE ID | NAME         | TITLE             | DEPARTMENT  |
|-------------|--------------|-------------------|-------------|
| 101         | John Doe     | Software Engineer | Engineering |
| 102         | Jane Smith   | Product Manager   | Marketing   |
| 103         | Mike Johnson | UX Designer       | Engineering |

Personnel Lists

## Geographic Domain



Company Geographical Data



Shipyard Facility Map



Heatmap

## Contextual Domain



Market and Business Intelligence

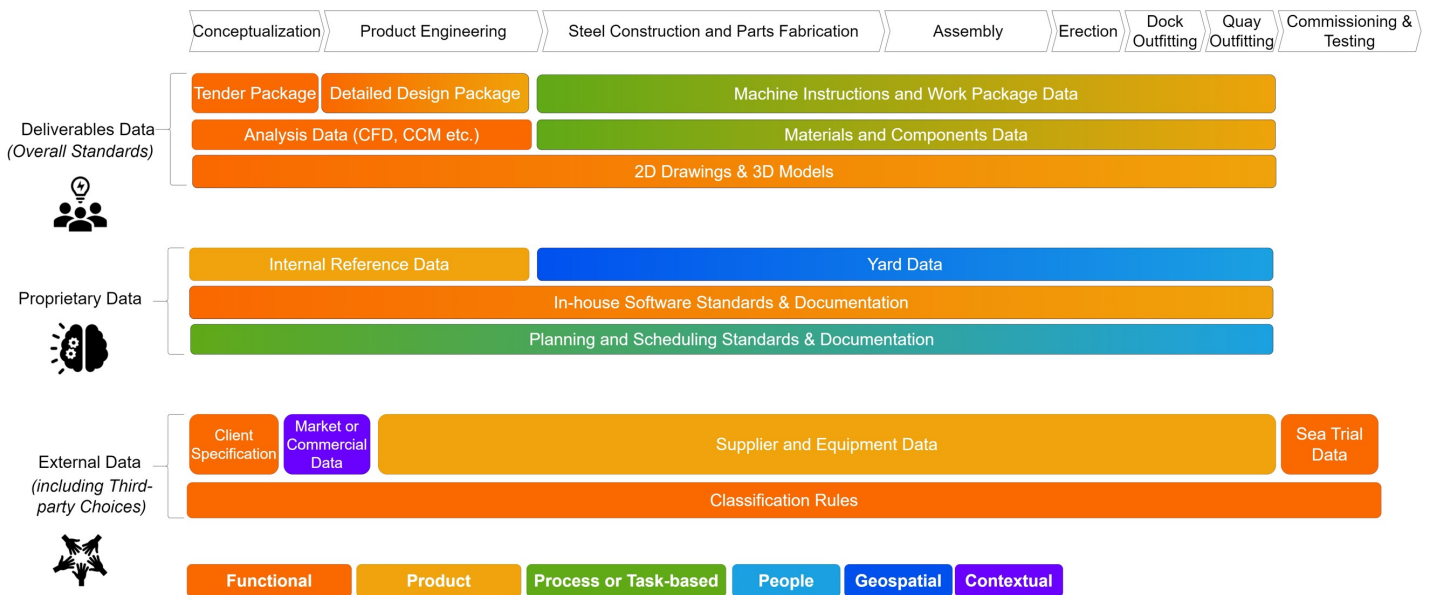


Socio-political Information



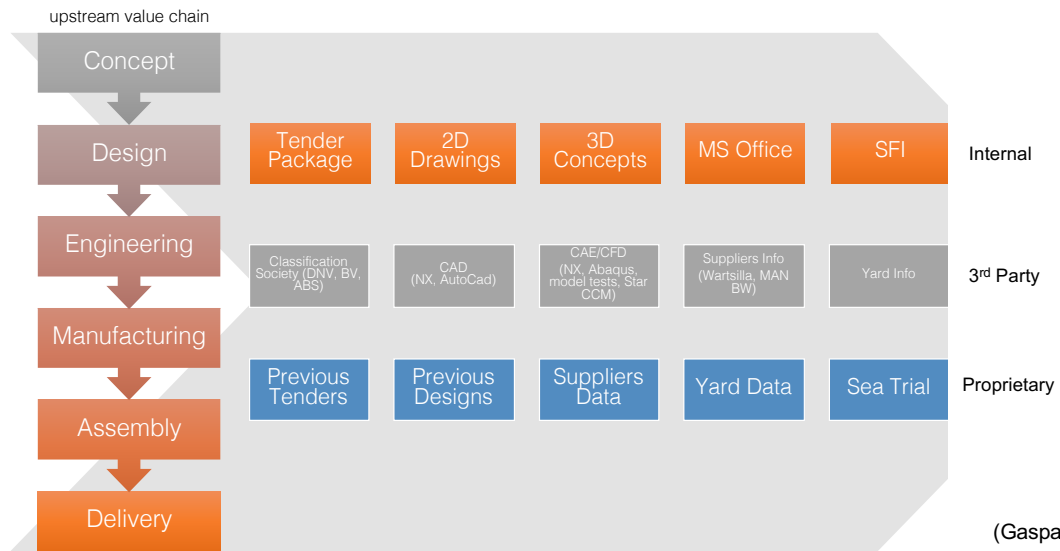
Tacit Data and Knowledge

Unfortunately, the integration of these domains faces 2 main challenges: (1) Domains are used concurrently across various stages of the entire lifecycle, and (2) these domains are exchanged across various stakeholders.



**These domains not only differ in contents and formats but also in their purpose and ownership.**

Integration solutions must also consider whether the information gathered is generated - from external third parties, or proprietary sources.



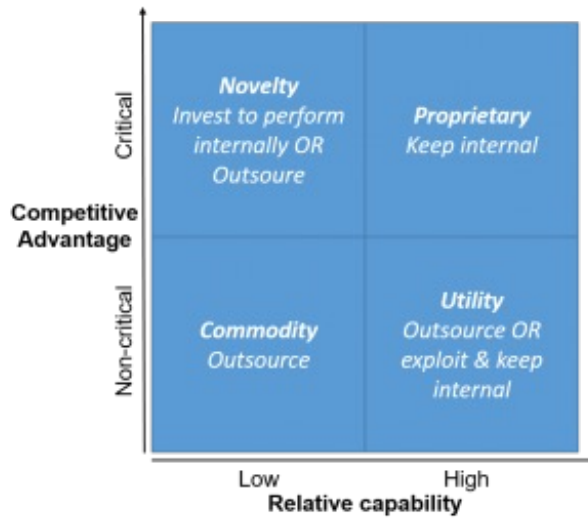
**Third-party sources or external parties may involve propeller suppliers, external designers, and classification societies, among others.**

|  |  |
|--|--|
| <p><b>MEKANISK UTSTYR</b><br/>Kraner   Vinsjer   Propeller<br/>Motorer   etc.</p> <p>WÄRTSILÄ   FRAMO   BRUNVOLL</p>                                 | <p><b>TEKNOLOGISKE TJENESTER</b><br/>Klassifisering   Ingeniørtjenester<br/>  Teknologisk FoU   Installasjon   etc.</p> <p>KAEFER ENERGY   DNV</p> |
| <p><b>ELEKTRISK OG ELEKTRONISK UTSTYR</b><br/>DP   Programvare   Spesialisert maskinvare   Utstyr for bro   etc.</p> <p>ABB   KONGSBERG   FURUNO</p> | <p><b>HANDEL</b><br/>Agenter   Grossister og distributører</p> <p>FRYDENBO   PEN CAT</p>   |
| <p><b>ANNET DRIFTSUTSTYR</b><br/>Maling   Smøremidler   Kabler<br/>  Kjettinger   Livbåter   etc.</p> <p>GLAMOX   NORDOX   JOTUN</p>                 | <p><b>DESIGN</b><br/>Skipsdesign</p> <p>ULSTEIN   LMG MARIN   WÄRTSILÄ</p>   |
| <p><b>VERFT</b><br/>Verft</p> <p>WESTCON   VARD   ULSTEIN</p>  |  |

(Menon Economics, 2023 [86])

## How can we properly integrate the standards used by different offshored yards, geographically disparate design offices, and contractors?

There are plenty of data risks that come hand in hand with the multi-organization happening across the entire lifecycle. These data risks include information theft and design reproduction.



(Every, 2015 [87])

## Multi-domain Taxonomy: Section Summary

Why is data and information management difficult to define in SD&SB?

- Integration challenges due to multiple data domains that transform, converge, or are used in parallel throughout life cycle. These domains include **Functional, Product, People, Geographic, Time, and Contextual domains**.
- The mapping of information and domain connections is not well-understood
- Information exchange capabilities, through legacy breakdown structures, are limited
- Data Management standards vary in different teams, different tools, and different phases

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- [20] NAVSEA. (2012). "SHIP DESIGN MANAGER (SDM) AND SYSTEMS INTEGRATION MANAGER (SIM) MANUAL." Technical report no. 2012
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Available at: <https://www.solitaireconsulting.com/2015/08/outsourcing-opportunity-threat/>

## Best Practices on Ship Design and Shipbuilding: Outline

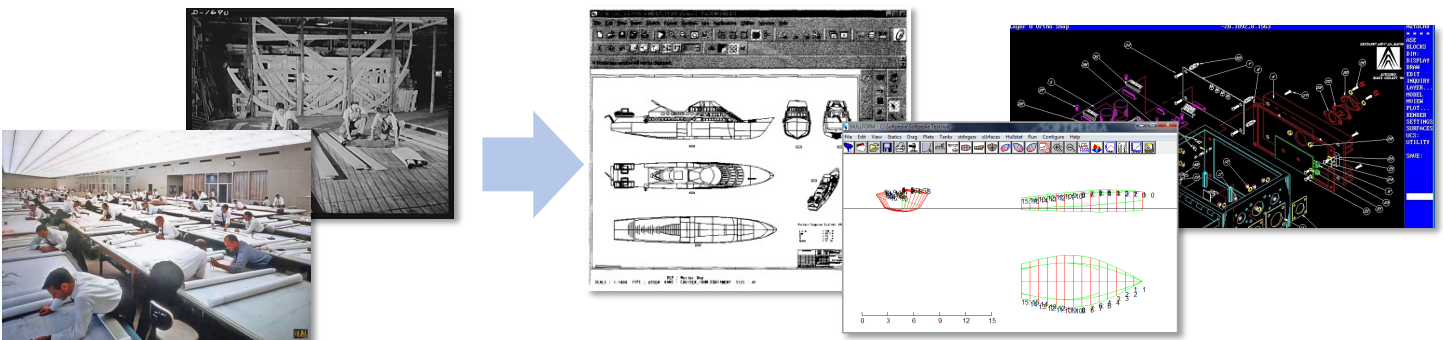
1. EU Shipbuilding and the SEUS Project
2. EU Place in Shipbuilding Market
3. The Ship Design and Shipbuilding Process
4. Multi-domain Taxonomy
- 5. The Ship Design and Shipbuilding Toolbox**
6. Distinctions in Ship Design and Shipbuilding
7. Single Source of Truth Concept or Attempt

## Historically, ship design and construction have been heavily reliant on design and modeling tools.

In the 1950s to 1970s, CAD/CAE/CAM systems for ship design were extremely popular, and developments in bespoke software solutions for naval architects happened at a rapid rate.

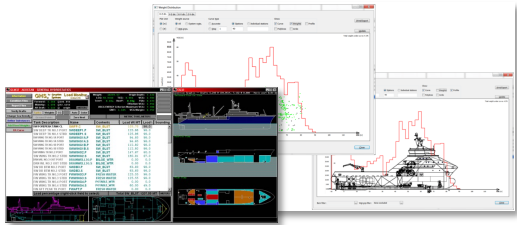
| Year    | Hardware  | Software  | End Users                            |
|---------|---|---|--------------------------------------|
| 1972–78 | Big computing centers, Main frames, Punched cards and alphanumeric terminals                | Independent programs, Sequential files, Batch processes                                 | Big shipyards                        |
| 1979–86 | Medium computing centers, Midi/Mini computers, Alphanumeric terminals and graphic terminals | Integrated programs, Medium level independent databases, Interactive processes          | Big and mid-size shipyards           |
| 1987–94 | Local area networks, Workstations, X-terminals, PCs   | Fully integrated programs, Single database, Interactive graphic processes, Open systems | Big, mid-size and small shipyards    |
| 1995–03 | Remote networks, PCs, Workstations, Parallel processors                                     | Windows environment, Object oriented programming, Improved inter-program data exchange  | All sizes of shipyards, Design firms |

(Ross, 2003 [53])

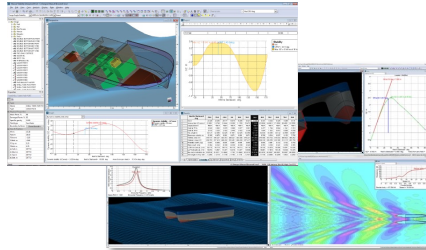


Since the 1980s, CAD (Computer Aided Design) and CAE (Computer Aided Engineering) solutions for ship design have been continuously developed and used to assist with specialized modeling and analysis tasks.

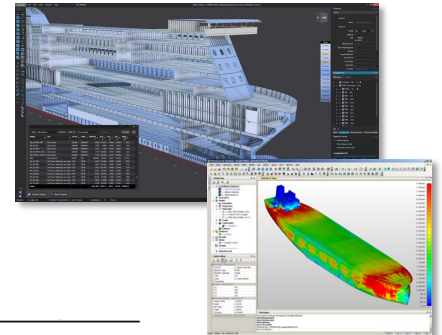
### Ship Hydrostatics



### Ship Hydrodynamics



### Ship Structure



| Program Name | Capability  |
|--------------|---|
| NavCAD       | Resistance and power prediction                                     |
| GHS          | Hydrostatics, stability, longitudinal strength                      |
| MAESTRO      | Structural design and optimization                                  |
| NASTRAN      | Finite element analysis (FEA)                                       |
| SafeHull     | FEA for yielding, buckling, and fatigue strength of ship structures |
| ShipWeight   | Weight and center of gravity estimation                             |

(Ross, 2003 [53])

## Typical Ship Design CAD and CAE Capabilities include:

### CAD Capabilities

- Hull Design
- Deck and Bulkheads Definition
- Compartmentalization
- Profiles and Arrangements
- Distributed Systems
- Drawings
- Engineering Analysis
- Early Stage Design

### CAE Capabilities

- Pipe Thermal
- Expansion
- Pipe and Pressure
- Flow
- Hydrostatics and
- Stability
- Volumes and Cargo
- Capacity
- Loading Conditions
- Speed/Power
- Plate Bending
- Electrical Loading
- Weights and Centers
- Structure
- Maneuvering and
- Control
- Propper
- HVAC
- Launching
- Seakeeping
- Noise Analysis

(Ross, 2003 [53])

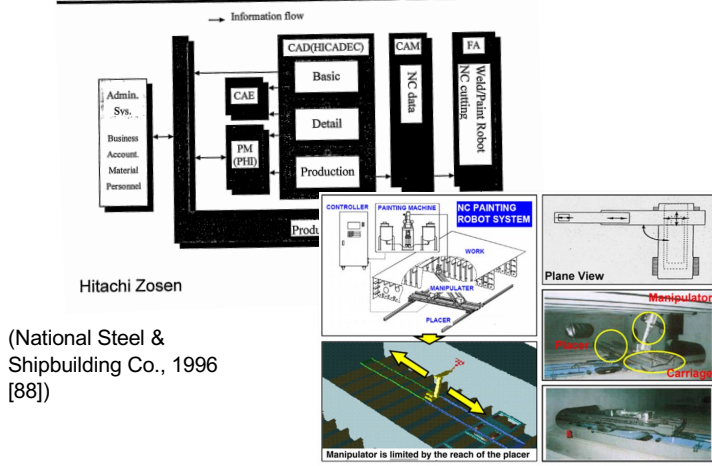
CSM/CAM (Computer-Aided Synthesis Modeling/Computer-Aided Manufacturing) applications have also been in use for steel and parts fabrication, and for ship assembly.

### 1970s CAM Tools

### Current

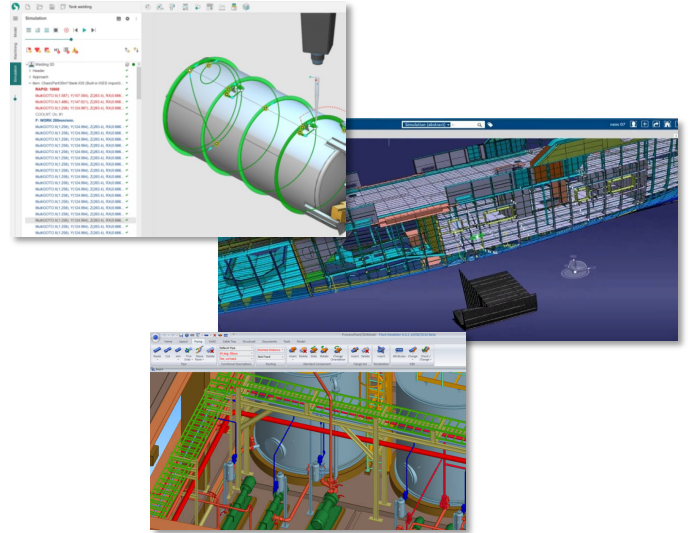
Figure 6.2

#### CIM Concept of Hitachi Zosen



Hitachi Zosen  
(National Steel & Shipbuilding Co., 1996 [88])

(Ku, et al., 2010 [89])



Source (Top, clockwise): Sprutcam, CATIA, CADMATIC

### Typical Ship Design CAM Functions:

#### CAM Capabilities

- |  |                             |
|--|-----------------------------|
| Accounting for weld shrinkage              | Paint Design and Monitoring |
| Dimension Control                          | Part Coding and Hierarchy   |
| Interface between product model and robots | Nesting                     |
| Robotic Programming                        | Plat and Profile Forming    |
| Production Management Support              | Pipe Bending                |
| Lifting Planning                           | Cable Length                |

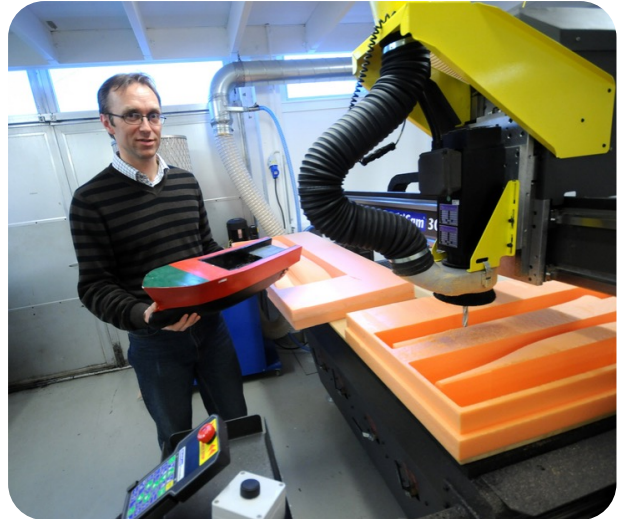
(Ross, 2003 [53])

Testing methodologies since the 1960s have greatly improved – from model hulls faired and fabricated manually to CNC-machined hull forms.

Model Test, 1960s



Model Test, 2010s



Given the high reliance on computer-aided tools, Information Integration has been critical in the industry to manage the data from CAD/CAE/CAM software. Systems Integrators and Product Data Managers are essential members of ship design teams.

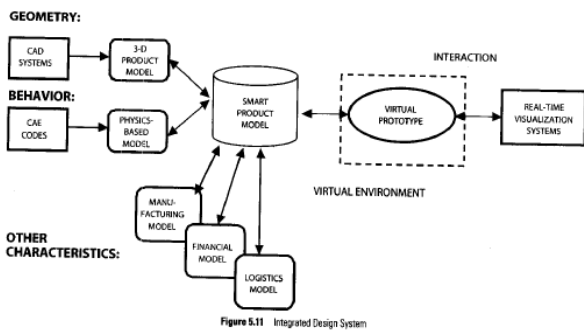
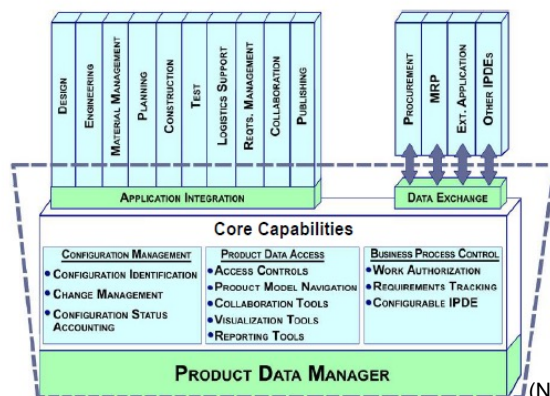


Figure 5.11 Integrated Design System

(Gale, 2003 [29])

Integration Design System

2003



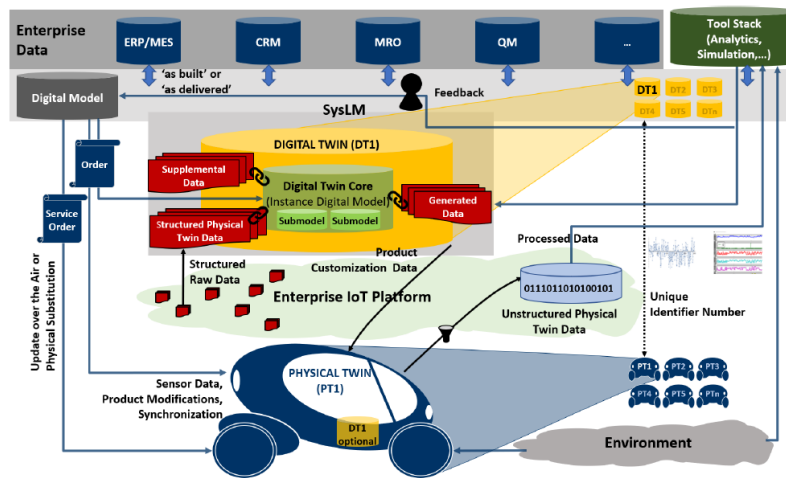
(NAVSEA, 2012 [20])

Design Environment for Ship Building (NAVSEA)

2012

Evolution of Integration Frameworks

With the popularity of digital twins and virtual prototypes, these frameworks may potentially expand to robust information architectures that involve enterprise solutions and real-time data.



(Eigner, 2021 [54])

SysML and Digital Twins  
Sample Framework for Manufacturing

## Evolution of Integration Frameworks

EU Shipbuilding and the SEUS Project

EU Place in Shipbuilding Market

The Ship Design and Shipbuilding Process

Multi-domain Taxonomy

The Ship Design and Shipbuilding Toolbox

Distinctions in Ship Design and Shipbuilding

Single Source of Truth Concept or Attempt

123

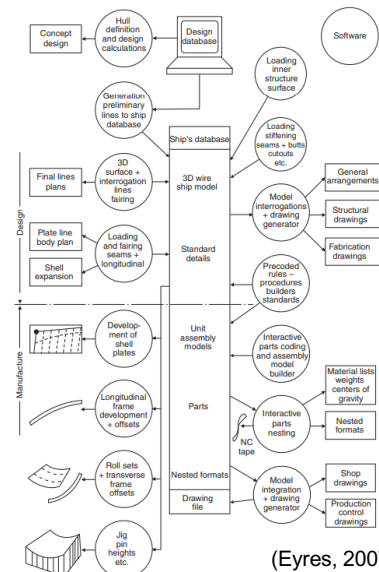
NTNU

A similar or equivalent idea to 'ship digital twin' has been envisioned since the 1970s in the form of a 'Ship Product Definition Model'.

According to Ross (2003) [53], 'an important aspect of product definition involves their three-dimensionality. Traditional ship design is carried out in 2D in preliminary stages and extended to 3D in detailed stages. The extension from 2D to 3D results in a large expenditure in time and labor...a product model enables designers to use the same model of a ship from the earliest stages of the design to production.'

## Capabilities of a Production Definition Model for Ship Industry (identified by Ross, 2003 [53])

|  |                                  |                         |
|--|----------------------------------|-------------------------|
| Single Integrated Database                 | Visualization of geometric model | Hull/Outfit Integration |
| GUI with a consistent format               | Build Strategy                   | Interface Checking      |
| Topological relationships among components | Generation of Drawings           | CAD/CAM                 |
| Macros                                     | Nesting                          | Multi-user capabilities |
| Parametric Definitions                     | BoM                              | Production Support      |
| Open Data Structure                        | Walkthroughs                     |                         |
| Generation of Structural Penetrations      | Part Data                        |                         |
|  | Libraries                        |                         |



(Eyres, 2007 [90])

EU Shipbuilding and the SEUS Project

EU Place in Shipbuilding Market

The Ship Design and Shipbuilding Process

Multi-domain Taxonomy

The Ship Design and Shipbuilding Toolbox

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## Future features and capabilities of a Ship Product Definition:

Is this achievable and can naval architects today have a tool with these functionalities?

TABLE 13.1V Full List of Future Requirements for Product Model Program

|   |  |  |
|---|--|--|
| <p><b>Design: Conceptual/Preliminary Design</b></p> <ol style="list-style-type: none"> <li>1. Concept/Preliminary Design Engineering Analysis Tools</li> <li>2. Reusable Product Model</li> <li>3. Develop Initial Build Strategy, Cost and Schedule Estimates</li> <li>4. Classification/Regulatory Body and Owner Compliance Support</li> </ol> <p><b>Design: Functional Design</b></p> <ol style="list-style-type: none"> <li>5. Connectivity Among Objects</li> <li>6. Tools to Develop Standard Parts, Endcuts, Cutouts and Connections</li> </ol> <p><b>Design: Detailed Design</b></p> <ol style="list-style-type: none"> <li>7. Automated Documentation</li> <li>8. Detail Design Engineering Analysis Tools</li> <li>9. Design for Fabrication, Assembly and Erection</li> <li>10. Linkage to Fabrication Assembly and Erection</li> <li>11. Automatic Part Numbering</li> <li>12. Interference Checking</li> <li>13. Linkage to Bill of Material and Procurement</li> <li>14. Weld Design Capability</li> <li>15. Coating Specification Development</li> <li>16. Definition of Interim Products</li> <li>17. Consideration of Dimensional Tolerances</li> <li>18. Context-Sensitive Data Representations</li> </ol> <p><b>Production: Fabrication Processes</b></p> <ol style="list-style-type: none"> <li>19. Processes to Cut/Form Structural Plates and Shapes</li> <li>20. Documentation of Production Processes</li> <li>21. Information Links to Production Work Centers</li> <li>22. Piece and Part Labeling</li> <li>23. Creation of Path or Process Programs for NC Machines and Robots</li> <li>24. Development of Interim Product Fabrication Instructions</li> <li>25. Simulation of Fabrication Sequences</li> </ol> | <p><b>Production: Joining and Assembly Processes</b></p> <ol style="list-style-type: none"> <li>26. NC Programs for Joining and Assembly</li> <li>27. Automated Subassembly/Assembly Processes</li> <li>28. Programmable Welding Stations and Robotic Welding Machines</li> <li>29. Locations Marking for Welded Attachments</li> <li>30. Definition of Fit-Up Tolerances</li> <li>31. Control of Welding to Minimize Shrinkage and Distortion</li> <li>32. Programming for Automated Processes</li> <li>33. Definition of Fit-Up Tolerances for Block Assembly Joints</li> </ol> <p><b>Production: Material Control</b></p> <ol style="list-style-type: none"> <li>34. Capabilities for Material Pick Lists, Marshalling, Kitting and Tracking</li> <li>35. Tracking of Piece/Parts Through Fabrication and Assembly</li> <li>36. Communication of Staging and Palletizing Requirements to Suppliers</li> <li>37. Documentation of Assembly and Subassembly Movement</li> <li>38. Handling and Staging of In-Process and Completed Parts</li> </ol> <p><b>Production: Testing and Inspection Guidelines</b></p> <ol style="list-style-type: none"> <li>39. Testing and Inspection Guidelines</li> </ol> <p><b>Operations Management: High-Level Resource Planning and Scheduling</b></p> <ol style="list-style-type: none"> <li>40. High Level Development of Build Strategy</li> <li>41. Order Generation and Tracking</li> <li>42. Performance Measurement</li> <li>43. Production Status Tracking and Feedback</li> <li>44. Inventory Control</li> <li>45. High Level Planning and Scheduling</li> </ol> | <p><b>Operations Management: Production Engineering</b></p> <ol style="list-style-type: none"> <li>46. Development of Production Packages</li> <li>47. Development of Unit Handling Documentation</li> <li>48. Parts Nesting</li> <li>49. Development and Issue of Work Orders and Shop Information</li> </ol> <p><b>Operations Management: Purchasing/Procurement</b></p> <ol style="list-style-type: none"> <li>50. Material Management</li> </ol> <p><b>Operations Management: Shop Floor Resource Planning and Scheduling</b></p> <ol style="list-style-type: none"> <li>51. Provision of Planning and Scheduling Information to Shops</li> <li>52. Work Order/Work Station Tracking and Control</li> <li>53. Detailed Capacity Planning for Shops and Areas</li> <li>54. Collect and Calculate Costs for a Major Assembly</li> </ol> <p><b>Umbrella: Umbrella</b></p> <ol style="list-style-type: none"> <li>55. Datacentric Architecture</li> <li>56. Computer-Automated as Well as Computer-Aided</li> <li>57. Interoperability of Software</li> <li>58. Open Software Architecture</li> <li>59. Accessible Database Architecture</li> <li>60. Remote Networking Capability</li> <li>61. Full Data Access (Read Only) to All Project Participants</li> <li>62. Assignment of Data Ownership</li> <li>63. User-Friendliness</li> <li>64. Enterprise Product Model</li> <li>65. Integration With Simulation</li> <li>66. Information Management</li> <li>67. Scalability</li> <li>68. Transportability</li> <li>69. Configuration Management</li> <li>70. Compliance With Data Exchange Standards.</li> </ol> |
|---|--|--|

(Ross, 2003 [53])

## Past & Nostalgia: From years of trying to integrate ship data, what are our major learnings and setbacks?

### Learnings

#### We now have the following capabilities:

- Quicker 2D / 3D design processes
- Reliable documentation of the whole ship design process
- Ability to process and explore several configurations during early stages
- Exporting and data exchange capabilities between formats
- Connection between design (drawing) with performance (analysis)
- Revision control capabilities
- Precise determination of modelling effects into hydrostatic and hydrodynamics of the design
- Parametrization and optimization of geometry and performance (via scripting languages)

## Past & Nostalgia: From years of trying to integrate ship data, what are our major learnings and setbacks?

### Setbacks

- 20+ years of promising integration
- Difficult & expensive to adapt and use new software
- Converging from format .XYX to .ABC means loss of data
- Adaption challenges from multiple parties:
  - Developers (closed & proprietary software)
  - Experienced engineers (resistance to change)
  - Classification Society (lack of easy way to document)
  - Young engineers (lack of parsimony)
  - Market (not willing to pay for innovation)
  - Academia (not training properly)

## What are the main features we need to consider when developing effective computational tools for ship design and shipbuilding industry?

### Computational tools for Ship Design and Shipbuilding

Use of computer algorithms, simulations, and data analysis to support and enhance engineering processes.

#### Features related to business:

- **Operations-oriented** – Ability to improve operations and processes
- **Cost and Efficiency** – Ability to reduce costs and enable on-time delivery
- **Innovation Enabling** – Ability to enable new and emergent designs and processes
- **What other metrics should be considered?**

#### Features related to usability:

- **2D / 3D Models** – Flexibility to reorient 2D/3D representations
- **Level of Detailing** – Flexibility to provide various degrees of detail
- **Analysis and Simulation** – Coupling capabilities with other analysis and simulation functionalities
- **Integration Capabilities** – Ease of connection or integration with other tools, formats, and Information
- **Data Handling** – Ease of Information management from storage, access, analysis, transformation, and sharing

For usability features, it is important to consider how the tools enable integrated and or fragmented design practices.

## Source of Truth (SoT) Spectrum

Fragmented design practices

Integrated design practices

Use of multiple sources  
Tools are focused on a specific or specialized task  
Decomposed Data / Info  
Requires Import / Export  
Exchanging coherence for freedom  
Loss of efficiency (converging files)

Single Source  
Tools are able to perform multiple tasks  
Encapsulated Data / Info  
Database Integrated  
Exchanging freedom for coherence  
Loss of opportunity (bounded options)



These usability features are not one-dimensional, and trade-offs need to be selected. These trade-off decisions will also vary based on the lifecycle phase.

|                          | 2D/3D   | Level of Detailing   | Analysis and Simulation   | Integration Capabilities  | Data and Handling   |
|--------------------------|---|--|---|---|---|
| 2D/3D                    | 2D/3D   | Comprehensive models with capacity to filter and extract multiple view points  | Model and analysis tools coupled together, with simulation on the go, promising possibility to optimize topology/arrangement              | All in one software, either able to provide most of the analysis, either able to incorporate older compatible models in to the larger system          | One file with multiple models, larger size  |
| Level of Detailing       | Every level of detailing requires a new model   | Level of Detailing   | Simulation of the whole model, with filter in specific parts and analysis of overall consequences. Time consuming and complex to analyse. | Flow of detailing, with zooming and filtering, with categories division such as taxonomy, size, ownership, spatial position, functional requirements. | Few files with large data (size), and zoom/filtering capabilities inside the software to delimit boundary at any stage.             |
| Analysis and Simulation  | A new model for every new analysis, with minimal relevant info required in each model | One simulation of one small part or portion of the whole, a new simulation for each time/ phase/ degree of hierarchy. Faster and simpler | Analysis and Simulation   | "All in one" software, such as FEM, CFD, dynamics, thermodynamics sharing the same set of inputs.   | Inputs and outputs shared among simulation. A single (or fewer) large data sets with multiple values and attributes to be filtered. |
| Integration Capabilities | Single software for one task, one model for each task                                 | Every level of detail has very defined borders, not connected in a flow (one file for each level)  | One simulation/ software for one type of behaviour, no connection with other simulations. Separated and individual inputs and outputs.    | Integration Capabilities  | Single or fewer files with simulation and results integrated. Better on see multi-domain consequences, harder to filter.            |
| Data Handling            | Individual files for each model, small size, large number of files                    | Separated data for every level, with defined amount of required data/ files to establish a level   | Very defined boundary of inputs and outputs. Every simulation has it's own data.  | Separated files, with separated analysis and results. Easy to filter, hard to see multi-domain consequences.  | Data Handling   |

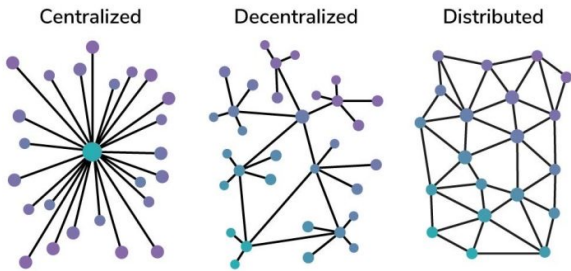
(Gaspar, 2019 [55])

Fragmented

Integrated

These practices reflect and further facilitate either decentralized, centralized, or distributed information systems. Decentralized information systems perpetuate information silos that do not correspond with each other.

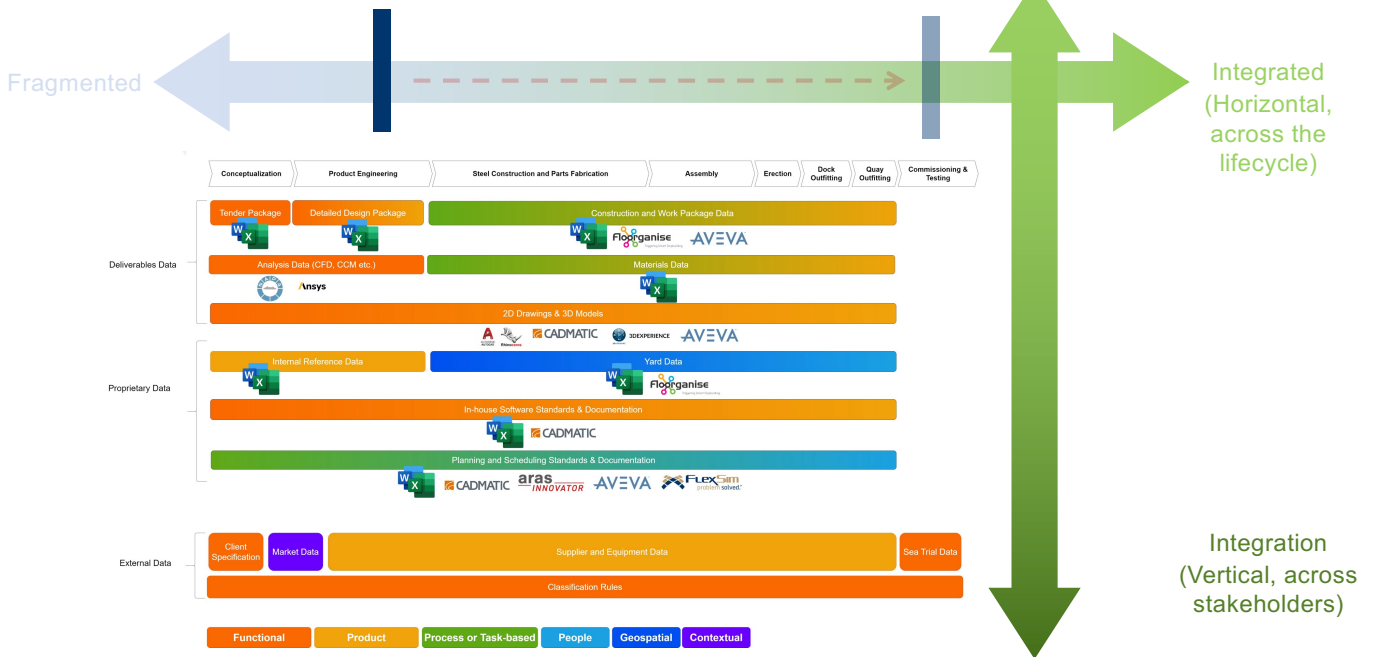
There are pros and cons to the different information systems. For instance, centralization of data allows for easier decision-making and data retrieval. Whereas with decentralization, the risk of single points of failure is decreased.



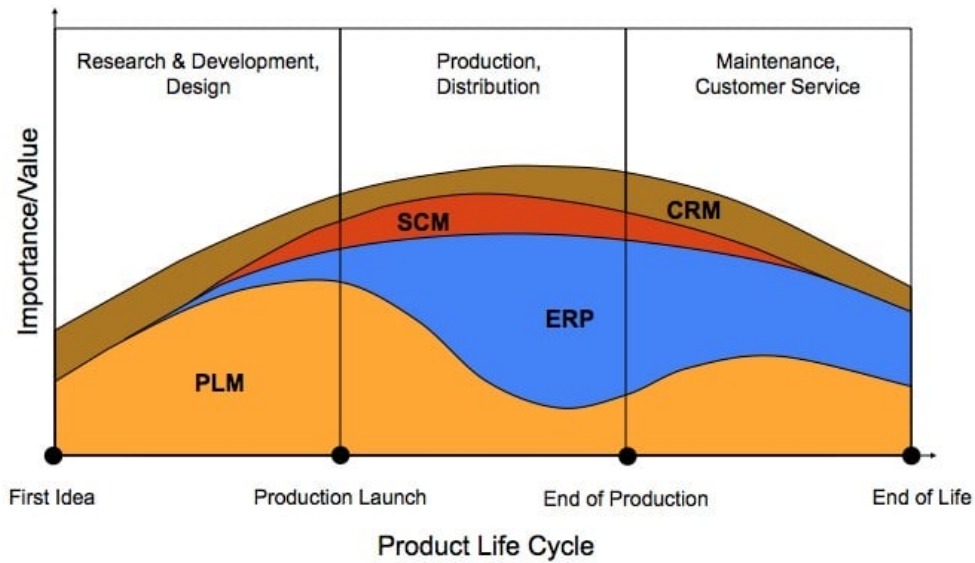
| Parameter                       | Centralized   | Decentralized  |
|---------------------------------|---|--|
| <b>Control</b>                  | Users lose ownership of their data as assets are transferred to central servers.  | Users retain ownership of their data.  |
| <b>Third-Party Intermediary</b> | A centralized exchange serves as a go-between for the buyer and the vendor. Due to the engagement of third parties, it charges operations fees. | Decentralized exchange serves as a "trustless" platform for transaction authorisation. Transactions are free of middleman fees.                              |
| <b>Single Point of Failure</b>  | A single point of failure in a centralized network can jeopardise the entire network's security.  | Because the information is disseminated throughout numerous blocks that are added together, a decentralized network does not have a single point of failure. |
| <b>User-Friendly</b>            | Beginners will find it simple and intuitive to operate.   | Complex, will require education/training.  |
| <b>Anonymous</b>                | Centralized networks cannot keep user data anonymous.   | Decentralized networks are built on the principle of anonymity.  |

(Ardana, 2022 [56])

With the current status quo of how ship design and shipbuilding activities are performed, what degree of integration would be feasible throughout the entire lifecycle?



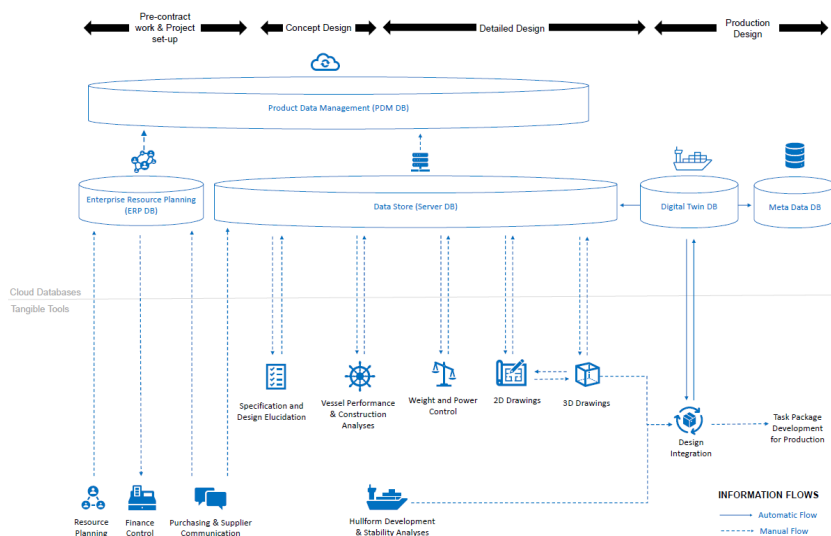
Currently, ship design companies use a combination of various business enterprise solutions to manage these integration needs and enable better planning and resource management. These enterprise tools include Enterprise Resource Planning (ERP) and Product Data Management (PDM).



(Gill, 2018 [91])

A common ship design data management solution today includes multiple databases and servers to manage technical and planning data.

However, these solutions still face common concerns in maintenance and usability, including the lack of automatic information flow processes.

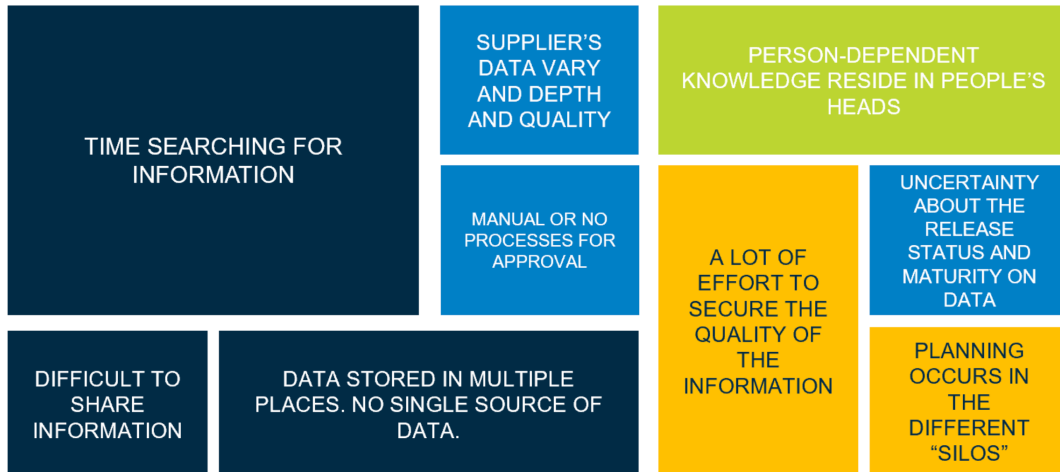


NOTE: These information map is an interpretation of the DMS needs of a company and may vary.

These concerns are echoed by the technical and administrative staff in SD&SB firms.

In Ulstein, for example, the persistence of information silos and difficulties in information exchange leads to inefficiencies in data retrieval.

## THE VOICE OF ULSTEIN



### Ship Design and Shipbuilding Toolbox: Section Summary

SD&SB Toolbox has traditionally evolved to cater to very technical design and modeling needs. Enterprise solutions are a modern attempt to handle the coordination and maintenance of these tools.

#### The current limitations of the existing toolbox include:

- Unclear degree of integration required (both horizontal across the lifecycle and vertical across various stakeholders)
- ERP and PDM solutions are able to meet limited functions that are bound to a single or only a few lifecycle phases
- Existing tools perpetuate highly disparate information systems
- Features such as the following are often not considered when deliberating what tools to adopt:
  - Flexibility to reorient 2D/3D representations
  - Flexibility to provide various degrees of detail
  - Coupling capabilities with other analysis and simulation tools

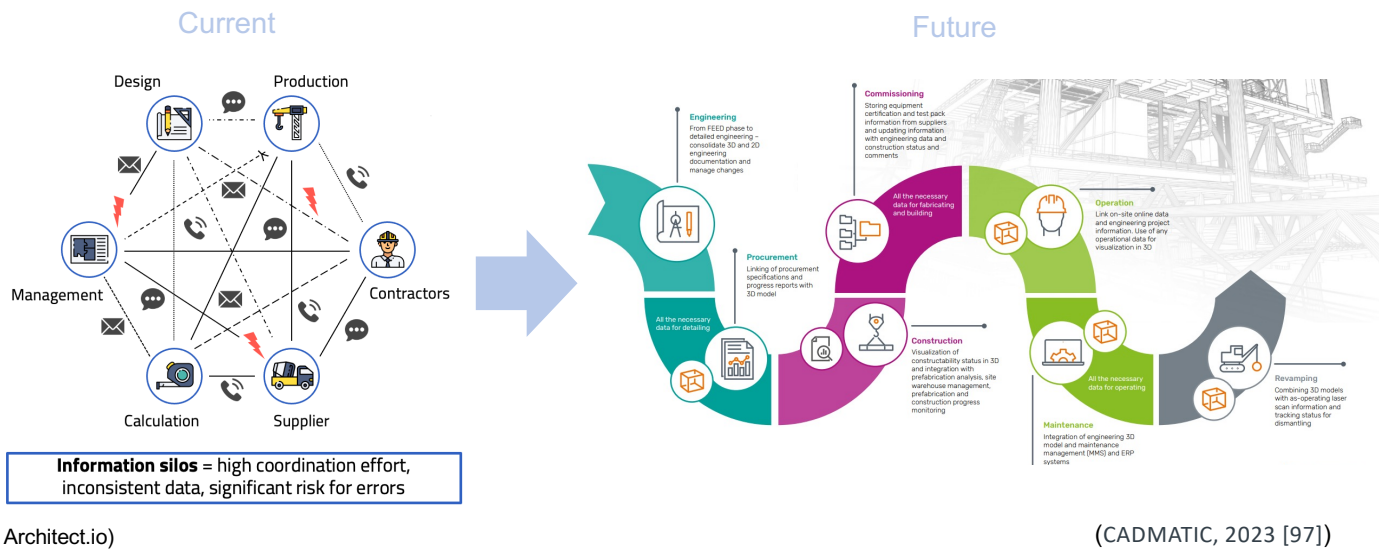
## References for The Ship Design and Shipbuilding Toolbox

- [29] Gale, P., 2003. Chapter 5: Ship Design Process. In: Lamb, ed. *Ship Design and Construction Volume I*.
- [20] NAVSEA, 2012. *Ship Design Manager and Systems Integration Manager Manual*.
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- [91] Gill, C., 2018. *Autodeck - PLM/PDM Adoption in your Company*. [Online]  
[Accessed 28 December 2023].

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## What solutions would enable better integration of the data across different lifecycle phases as well as vertical coordination of different stakeholders?



## The digital twin trajectory was originally designed to complement Project Lifecycle Management (PLM).

Initially, the digital twin concept was developed to model how physical and virtual systems should interface, naturally leading to the development of tools for the management of product data. Today, PLMs help companies to capture, codify, process, and communicate product knowledge across their organizations.

### Conceptual Ideal for PLM

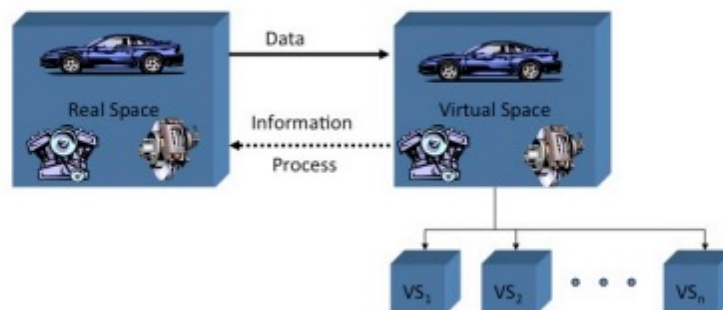
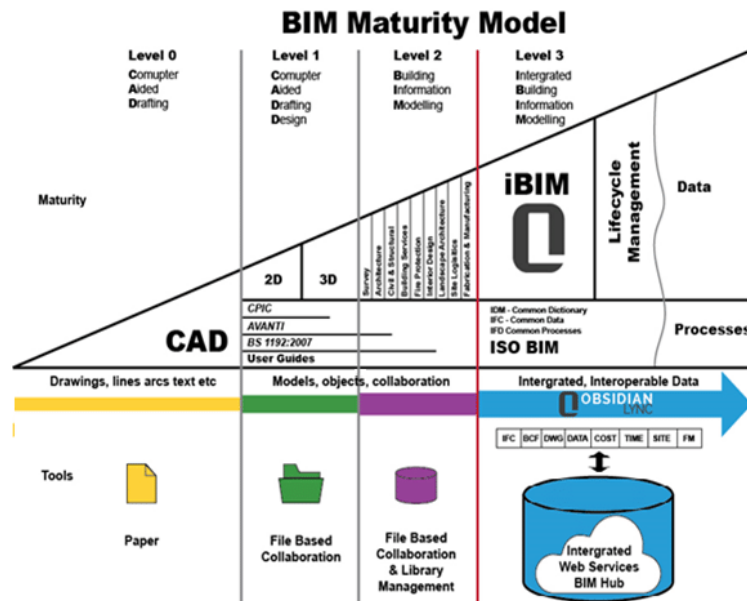


Figure 3

Dr. Michael Grieves, University of Michigan, Lurie Engineering Center, Dec 3, 2001

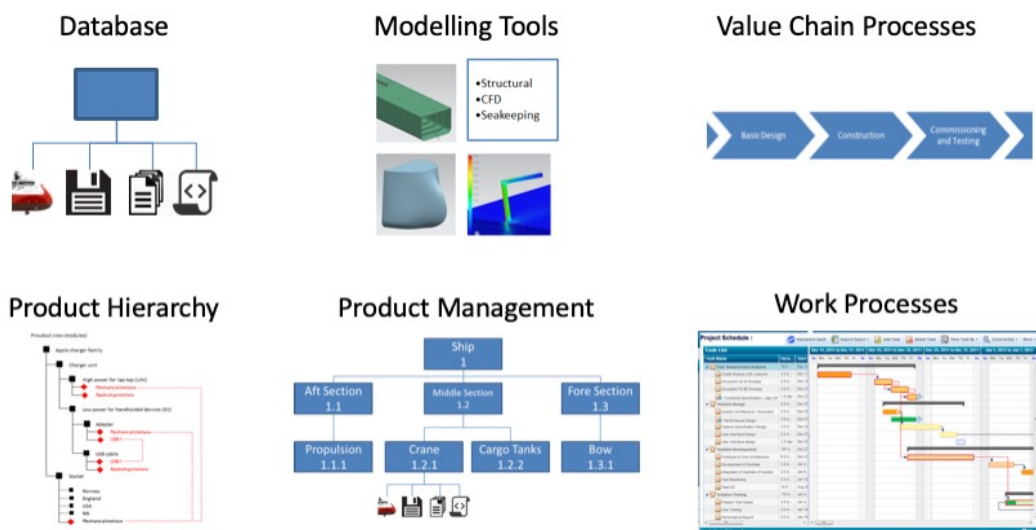
(Grieves, 2016 [92])

Parallel models exist in other industries. Building Model Information (BIM) in construction has the longterm intent of capturing building data and processes in an integrated and interoperable manner.



(Barlish & Sullivan, 2012 [93])

The potential of PLM and future hopes cover not only product data, but also database management, modeling tools, and process management.



(Andrade et al., 2015 [64])

# Examples of PLM software with functions that are mentioned in this report, in the ship building industry.

## Siemens PLM Software

### Optimize your product lifecycle

Customers demand innovative and sustainable products, produced at a premium quality, with a quick time to market. How can you rapidly develop and deliver top-notch products while smoothly navigating a range of process complexities? Use product lifecycle management (PLM) software to connect teams, data and processes so you can tackle product development complexity easier, faster and at scale.

As reported by Lifecycle Insights:

**59%**

59% of companies report that product development complexity is increasing.

**53%**

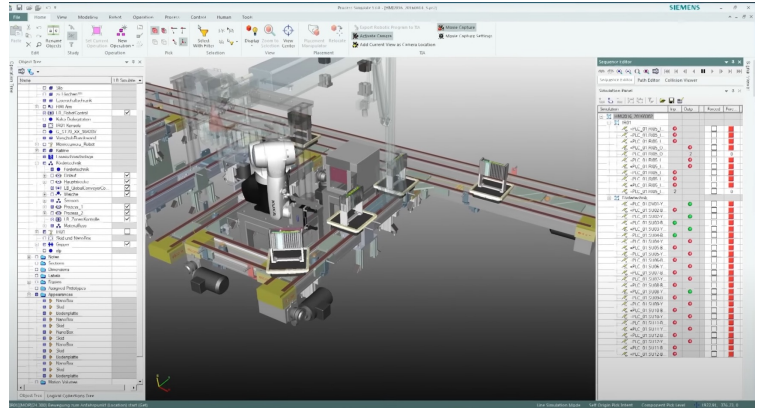
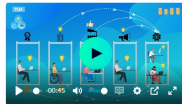
53% of companies identify satisfying target requirements as a primary issue.

**46%**

46% of companies see fewer than six in ten of their product development projects meet their launch or delivery deadlines.

### How can PLM on the cloud help you deliver innovative, high-quality products, while keeping costs reasonable and ensuring a fast return on investment?

Implement a PLM solution to build a data and collaboration system that will enable your entire organization to work as a single team, in real time, with one source of truth: from design to prototyping to testing to manufacturing and beyond.



<https://www.sw.siemens.com/en-US/solutions/product-lifecycle-management-plm/>

EU Shipbuilding and the SEUS Project

EU Place in Shipbuilding Market

The Ship Design and Shipbuilding Process

Multi-domain Taxonomy

The Ship Design and Shipbuilding Toolbox

Distinctions in Ship Design and Shipbuilding

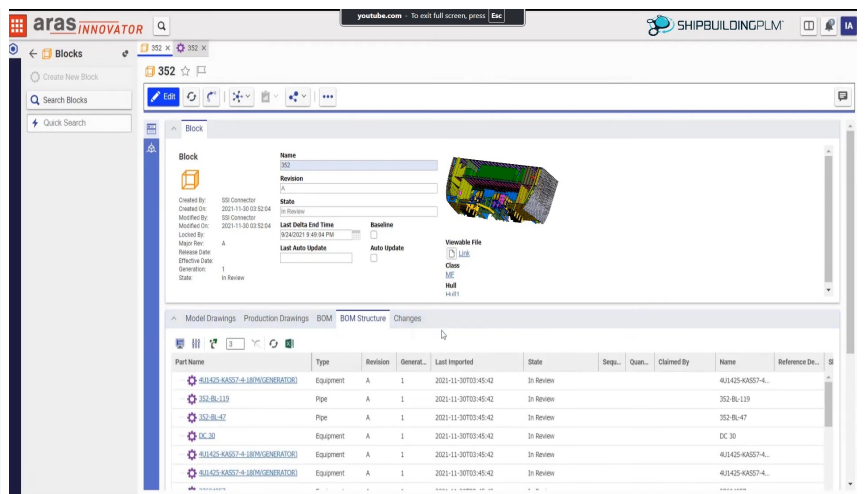
Single Source of Truth Concept or Attempt

143



# Examples of PLM software with functions that are mentioned in this report, in the ship building industry.

## SSI ShipbuildingPLM



<https://www.ssi-corporate.com/products/shipbuildingplm/>

EU Shipbuilding and the SEUS Project

EU Place in Shipbuilding Market

The Ship Design and Shipbuilding Process

Multi-domain Taxonomy

The Ship Design and Shipbuilding Toolbox

Distinctions in Ship Design and Shipbuilding

Single Source of Truth Concept or Attempt

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# A PLM tool can be coupled with other enterprise solutions such as ERP/PDM and other CAD/CAE/CAM software.

## Development of Improved Shipbuilding Process & Data Management



We are developing a solution for the shipbuilding industry

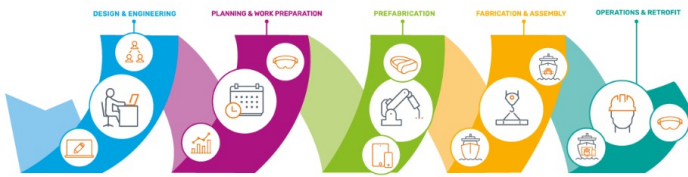
CADMATIC Wave is a process and data management solution designed to tackle these shipbuilding industry-specific issues. Created via a strategic partnership between Cadmatic and CONTACT Software, it serves as the shipyard's central hub, harnessing the power of digital assets and processes to ensure optimal efficiency, profitability, and quality.

Product development is in progress. We will provide more information in near future.

### Why CADMATIC Wave is unique

|  |   |   |
|--|---|---|
| <p><b>Shipbuilding-specific process and data management</b></p> <p>While other industries may benefit from generic systems, shipbuilding demands specialized process and data management solutions. Every vessel is a unique project with its own set of challenges, requiring focused tools for effective management.</p> | <p><b>Data-driven over document-driven</b></p> <p>In traditional shipbuilding, the vast number of documents can create bottlenecks and increase the risk of errors. CADMATIC Wave shifts the focus to data, allowing for seamless and reliable project execution.</p> | <p><b>Lifecycle management beyond construction</b></p> <p>Extend your capabilities beyond the shipyard and open new revenue streams. CADMATIC Wave's digital twin functionality helps ship owners and operators effectively manage a vessel throughout its lifetime, from retrofits to regular maintenance.</p> |
|--|---|---|

### Transform your shipyard with CADMATIC Wave

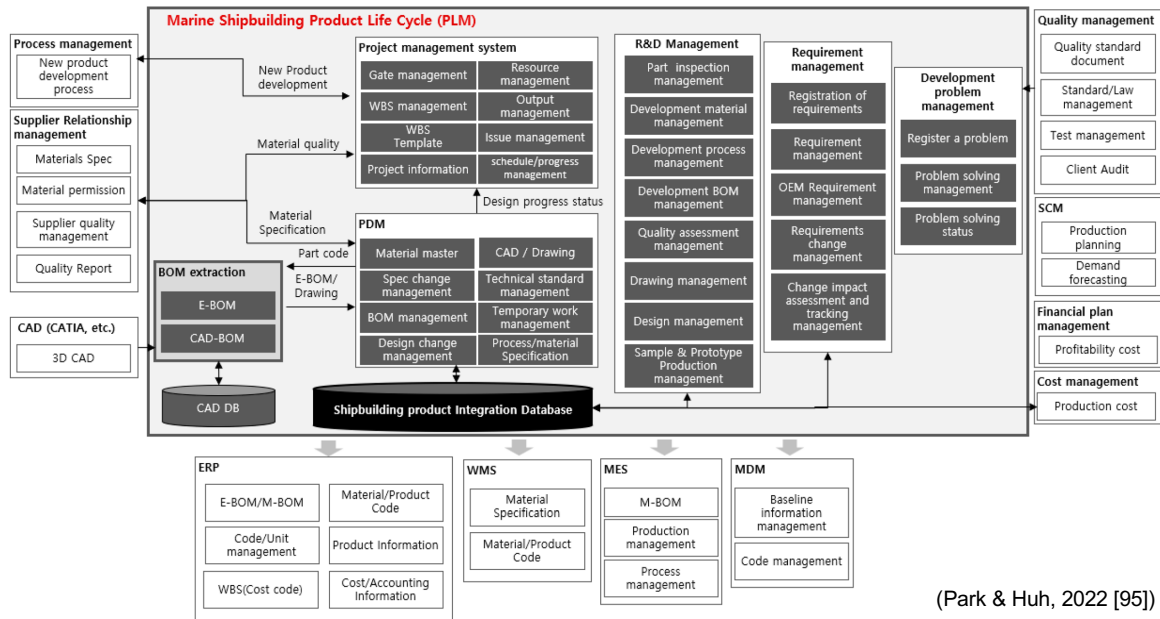


|   |   |  |
|---|---|--|
| <p><b>Boost efficiency and cut costs</b></p> <p>Synchronize your resources, minimize redundancies, and execute projects ahead of deadlines.</p> | <p><b>Enhance collaboration and transparency</b></p> <p>Break down the barriers between departments and achieve synergy in workflows.</p> | <p><b>Make better decisions</b></p> <p>Equip your team with the advanced tools they need for proactive and informed decision-making.</p> |
|---|---|--|

(CADMATIC, 2023 [97])

# Several academic attempts have been made focused on theoretically defining a PLM-centric approach for Shipbuilding.

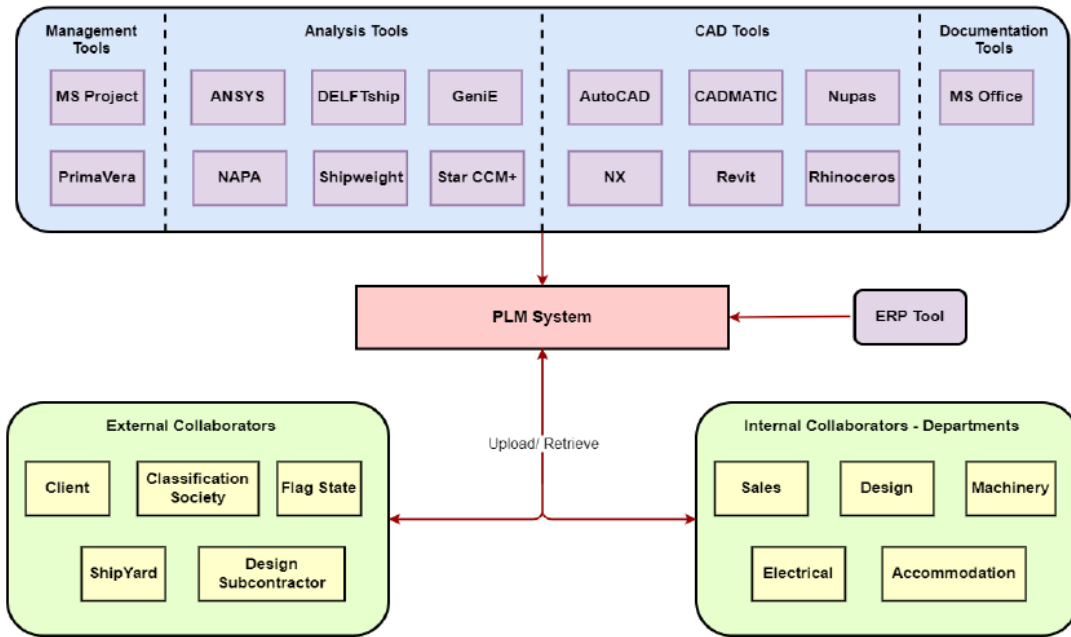
## PLM Framework (Sample #1)



(Park & Huh, 2022 [95])

NOTE: These information map is an interpretation of the DMS needs of a company and may vary.

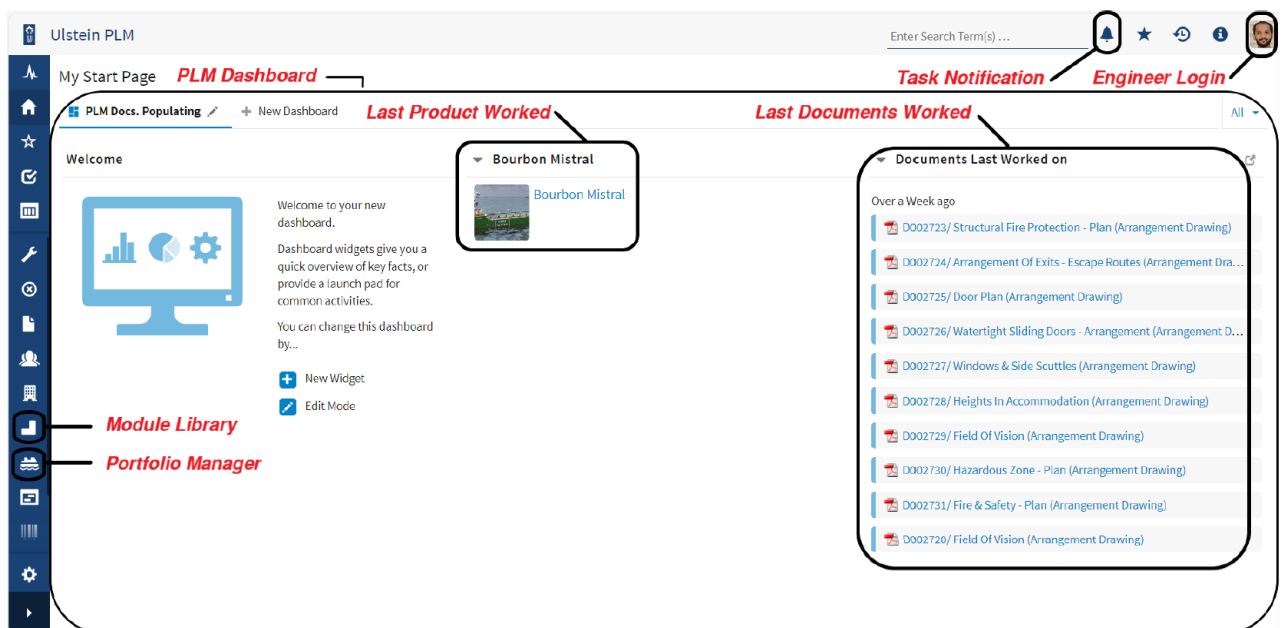
## PLM Framework (Sample #2), Ulstein Architecture



NOTE: These information map is an interpretation of the DMS needs of a company and may vary.

(Thamby, 2023 [26])

## PLM Framework (Sample #2), Ulstein Interface



(Thamby, 2023 [26])

## PLM Framework (Sample #2), Ulstein Interface

**Document Manager**

| O. | S. | I. | Document No. | Title   | SH 1 | SH 2 | SH 3 | Main Category                       | Category            | Department                 |
|----|----|----|--------------|---|------|------|------|-------------------------------------|---------------------|----------------------------|
|    |    |    | D001206      | General Arrangement                                 | 1    | 10   | 101  | Drawings / Mechanics                | General Arrangement | Engineering                |
|    |    |    | D001209      | Tank Plan   | 1    | 10   | 101  | General                             | Tank Plan           | Engineering                |
|    |    |    | D001210      | Building Specification                              | 1    | 10   | 100  | Product and Technical Documentation | Technical Datasheet | Engineering                |
|    |    |    | D001211      | Fact Sheet  | 1    | 10   | 100  | Product and Technical Documentation | Technical Datasheet | Engineering                |
|    |    |    | D001212      | Outline Specification                               | 1    | 10   | 100  | Product and Technical Documentation | Technical Datasheet | Engineering                |
|    |    |    | D001213      | Single line diagram                                 | 8    | 67   | 871  | Electrical / Electronic Engineering | Layout Drawing      | Engineering Electrical     |
|    |    |    | D001214      | Docking Plan  | 1    | 14   | 144  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001215      | Anchor And Chain - Arrangement                      | 2    | 26   | 266  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001216      | Arrangement Working Decks                           | 2    | 26   | 267  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001217      | Layout Wheelhouse Roof And Mast                     | 4    | 41   | 418  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001218      | Navigation and Signal Light - Layout                | 4    | 42   | 427  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001219      | Mooring Deck Forward/AR/Emergency Towing - Layout   | 4    | 43   | 433  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001220      | Lifesaving Equipment/Life Boat & Life Raft - Layout | 5    | 50   | 503  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001221      | Hazardous Zone - Plan                               | 1    | 10   | 103  | Drawings / Mechanics                | Arrangement Drawing | Engineering Machinery ...  |
|    |    |    | D001222      | Fire & Safety - Plan                                | 5    | 50   | 501  | Drawings / Mechanics                | Arrangement Drawing | Engineering Machinery ...  |
|    |    |    | D001223      | Structural Fire Protection - Plan                   | 5    | 50   | 500  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001224      | Arrangement Of Exits - Escape Routes                | 5    | 50   | 503  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001225      | Door Plan   | 5    | 51   | 517  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001226      | Watertight Sliding Doors - Arrangement              | 5    | 51   | 513  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001227      | Windows & Slide Scuttles                            | 5    | 51   | 515  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001228      | Heights In Accommodation                            | 5    | 59   | 590  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |
|    |    |    | D001229      | Field Of Vision                                     | 5    | 59   | 590  | Drawings / Mechanics                | Arrangement Drawing | Engineering Outfitting ... |

(Thamby, 2023 [26])

### However, there are several concerns with the application and adoption of PLM:

- Additional work to add existing data in the new format/standard/library
- Lack of ship design terms, tools, and methodologies incorporated in the available tools, with the designer adapting to a more mechanical engineering approach to traditional ship design analyses.
- Lack of seamless integration with third-party ship design tools
- Proprietary and closed software package, constraining customization
- High cost to acquire, install, train personnel, and keep servers running.
- Resistance to experienced engineers to use a new tool
- Risk of being locked to a system, and losing independence if features and license terms change
- Ignore that individuals have different preferences on how they solve the problem and that a certain methodology proposed by the PLM system is not the most effective among the ship design community
- Inability to incorporate commonly used ship design files (data types) in the database, as well as to open the large diversity of CAD files
- Forget that Word, Excel, and PPT are key means to compile and share information, forcing internal reports

## Perceptions of PLM usage vary per person in SD&SB firms.

For example, in Ulstein, there are positive perceptions of how PLM contributes to better control of ship design data. However, there are concerns with the rigid documentation required.

### Naval architect

- Currently the software is too slow
- Concerned about higher work load with 3D model
- Need CAD engineers to maintain library/items
- Positive to shared library with searchable attributes
- Positive to workflows and project control
- Re-use

### Machine/electrical

- Concerned with more rigid documentation control
- Question the need of documentation early in the projects
- Positive to searchable attributes

### Weight engineer

- Positive to added information ( BOM, Weight of components, Center of gravity, Technical specification of components, volumes)
- Walk-through the vessel

### Stability engineer

- Import of 3D model
- More accurate weight estimation

### Hydro

- Parametric modelling
- No export of hull lines

### Sales

- Better control of price – reduced margins
- 3D model looks better – easier communication with customer

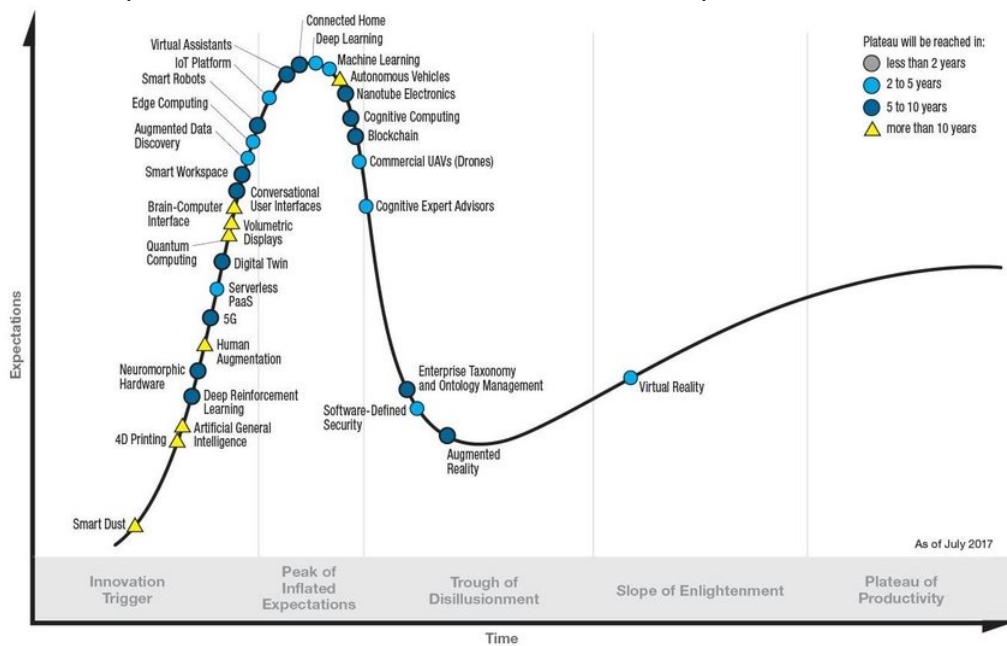
### SCM

- Better control of what the naval architect have put in the vessel

(Hovden, 2017 [22])

## Fears and expectation regarding the unknown

In the path towards digital transformation, it is common to face a trough of disillusionment. Are there ways the industry can de-risk the exploration of new solutions or better define expectations?



(Gartner, 2017 [96])

## How to arrive at an optimistic future for ship design and shipbuilding?

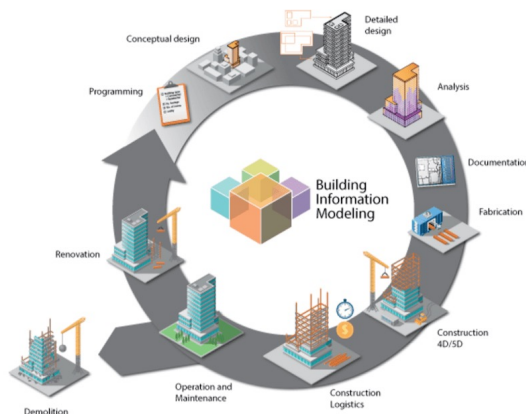
- Re-use and build up on former designs, allowing the designer to fetch former designs from a database, building up new concepts based on the new information
- Re-using advanced 3D models for many value-chain phases (sales, concept, basic, construction).
- Keep the collected and analysed data as accessible as possible during the design process
- Access to the analyses made during the design process, options, and behaviour of the systems under the multiple operational scenarios studied, without the filter of a locked proprietary system.
- Must integrate smartly the data used as input and gotten as output from the available ship design tools, as well as incorporating empirical knowledge from stakeholders.

## What frameworks and practices from other industries would be worth incorporating to a computational tool/solution for the European SD&SB market?

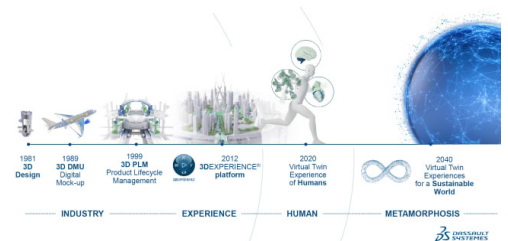
### DevOps & Open Standards



### Construction (BIM)



### Aerospace (3D DMU)



## Transferrable DevOps Elements



- Data (and code/methods) available to designer and users
- Version control of files and infrastructure to enable collaboration and rollbacks
- Multi-hierarchical data, allowing plural data tags, such as functional/spatial/economic hierarchies, multiples level via *tags* or object properties (main machinery can be part of a propulsion system in one division (functional) and part of the hull in another division (physical)).
- Data format as open as possible, including numbers (e.g. simulations inputs, codes and results) and models (e.g. 2D and 3D models in open-source formats, such as SVG or STL)
- Collaborative storage and editing capabilities, in line with modern software repositories, such as GitHub, with features such as versioning, tracking of changes, reviews, ownership levels, task assignments, automatic documentation, web interface, and intelligent search algorithms.
- Tools to open and manipulate the available data must be accessible to all stakeholders, without the necessity of large installation packages or extensive server configuration
- Continuous integration of collected and generated data, across the lifecycle

## References for Distinctions in Ship Design and Shipbuilding

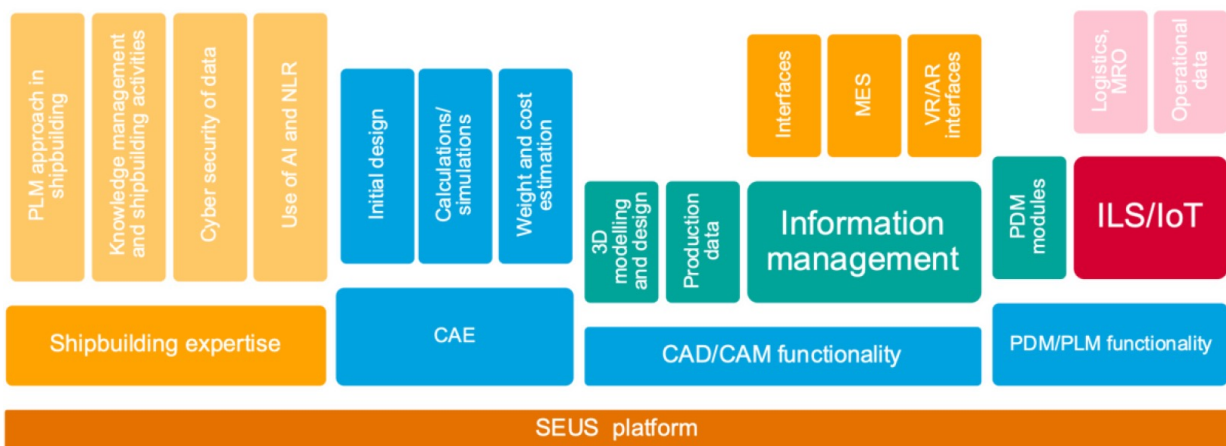
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- [96] Gartner, 2017. *SmarterWithGartner*. [Online]  
[Accessed <https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017> November 2023].
- [97] CADMATIC. (2023). *eShare: Change the way you think about digital information*. <https://www.cadmatic.com/en/resources/publications-and-brochures/cadmatic-information-management-plant-design-en.pdf>

## Best Practices on Ship Design and Shipbuilding: Outline

1. EU Shipbuilding and the SEUS Project
2. EU Place in Shipbuilding Market
3. The Ship Design and Shipbuilding Process
4. Multi-domain Taxonomy
5. The Ship Design and Shipbuilding Toolbox
6. Distinctions in Ship Design and Shipbuilding
7. **Single Source of Truth Concept or Attempt**

### SEUS Proposal: Smart Platform Desired Elements

As part of the SEUS proposal, certain desired elements are considered covering expertise in ship design and shipbuilding, CAD/CAE/CAM functionalities, and information management.



(Gaspar et al., 2023 [98])

## Current & Next Steps

As part of the development of the WP1, the following steps are planned to supplement the findings from the literature review and research.

- 1 Engage with ship designers and yards to understand their concept of an SSoT & PLM Solution**
- 2 Synthesize feedback to help identify PLM functionalities needed
- 3 Continuously update the Best Practices draft with results from collaborative testing with ship designers, shipyards, and software developers

## Ongoing Interview

Survey and interviews are ongoing with shipyard partners to determine gaps in research findings, and supplement SD&SB process maps found in literature reviews.

### Introduction

1. Please describe your role at the company.
2. How many years have you been working within or in connection with the Maritime Industry?

### Activity-based Questions

3. What are your three main activities?
4. Please describe the workflow associated with each of these activities.
5. For each of these activities, who do you interact with? (i.e. immediate team, department, company, and external parties)
6. For each of these activities, please describe how information is exchanged.
7. For each of these activities, what communications tools do you use?
8. For each of these activities, what digital tools do you use? How fragmented or integrated are these tools?
9. For each of these activities, how do you:
  - a. Access data (or retrieve data)
  - b. Store data
  - c. Transform data (or process, analyze, and handle data)
  - d. Share data within your immediate group, department, company, and external parties
10. What are the risks, uncertainties, and issues that you encounter when accessing, storing, transforming, and sharing data more efficiently?

## Ongoing Interview

Survey and interviews are ongoing with shipyard partners to determine gaps in research findings, and supplement SD&SB process maps found in literature reviews.

11. Please rate how these challenges affect the efficiency of your group's work. (1 – Applicable to 5 – Does not apply)

- Excessive time spent searching for information.
- Difficulty sharing information.
- No single source of data.
- Suppliers' data vary in depth and quality.
- Manual or no processes for approval.
- Person-dependent knowledge resides in people's heads.
- A lot of effort spent securing the quality of the information.
- Uncertainty about the release status and maturity of data.
- Planning occurs in different 'silos'.

13. How critical is it for you to access data in these domains? (1 – Applicable to 5 – Does not apply)

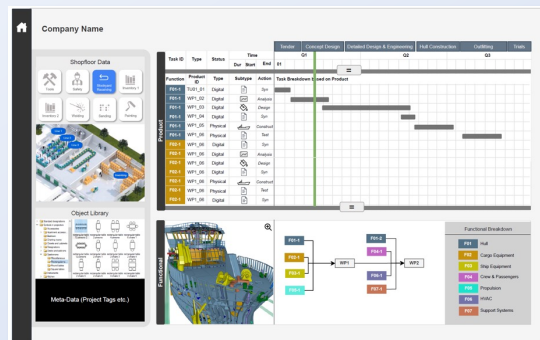
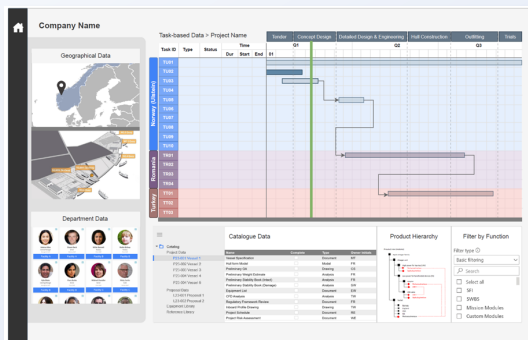
- Functional or Systems-based Data
- Product Data
- Process or Task-based Data
- People or Human Resource Data
- Geographic Data
- Contextual Data

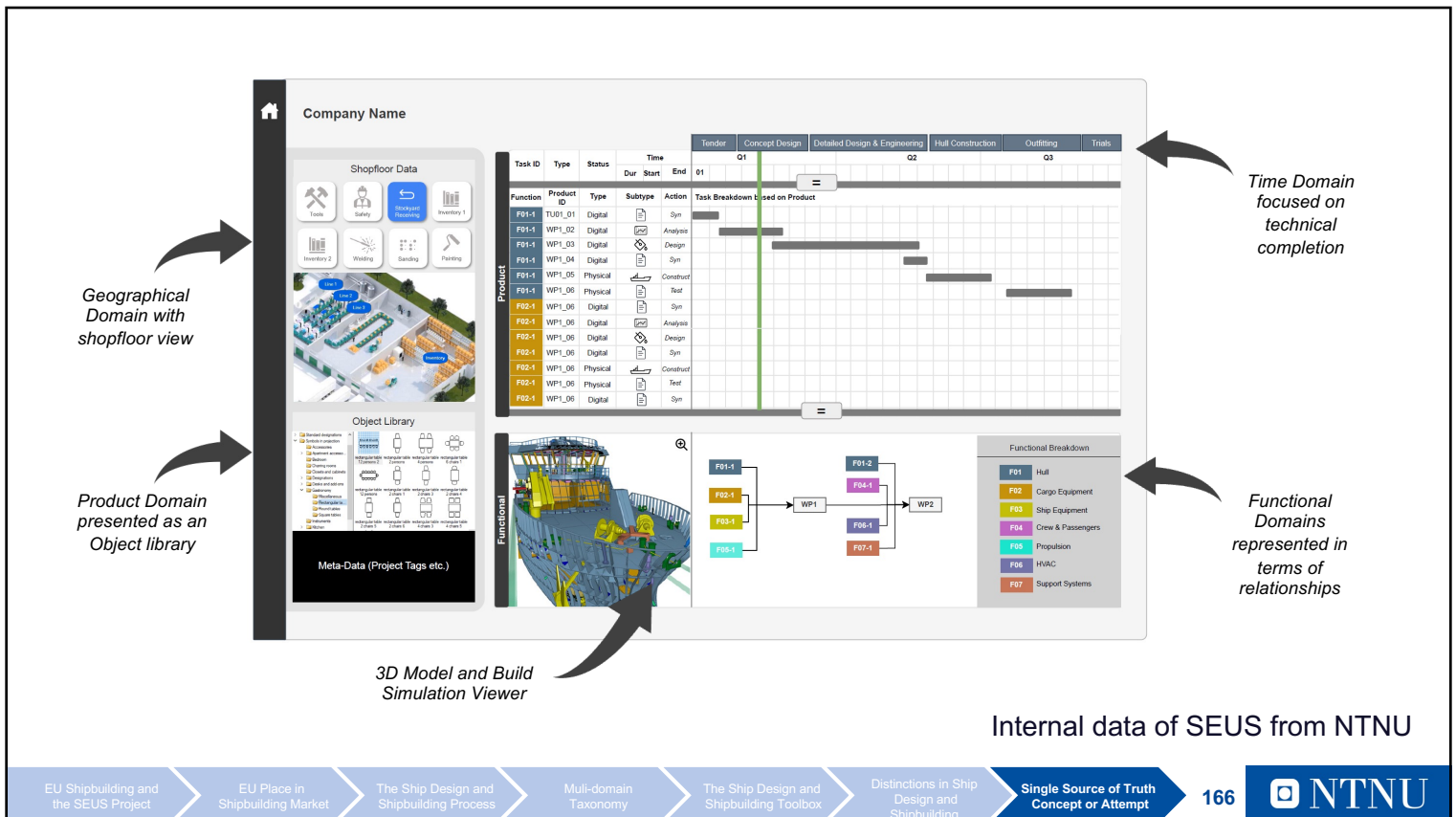
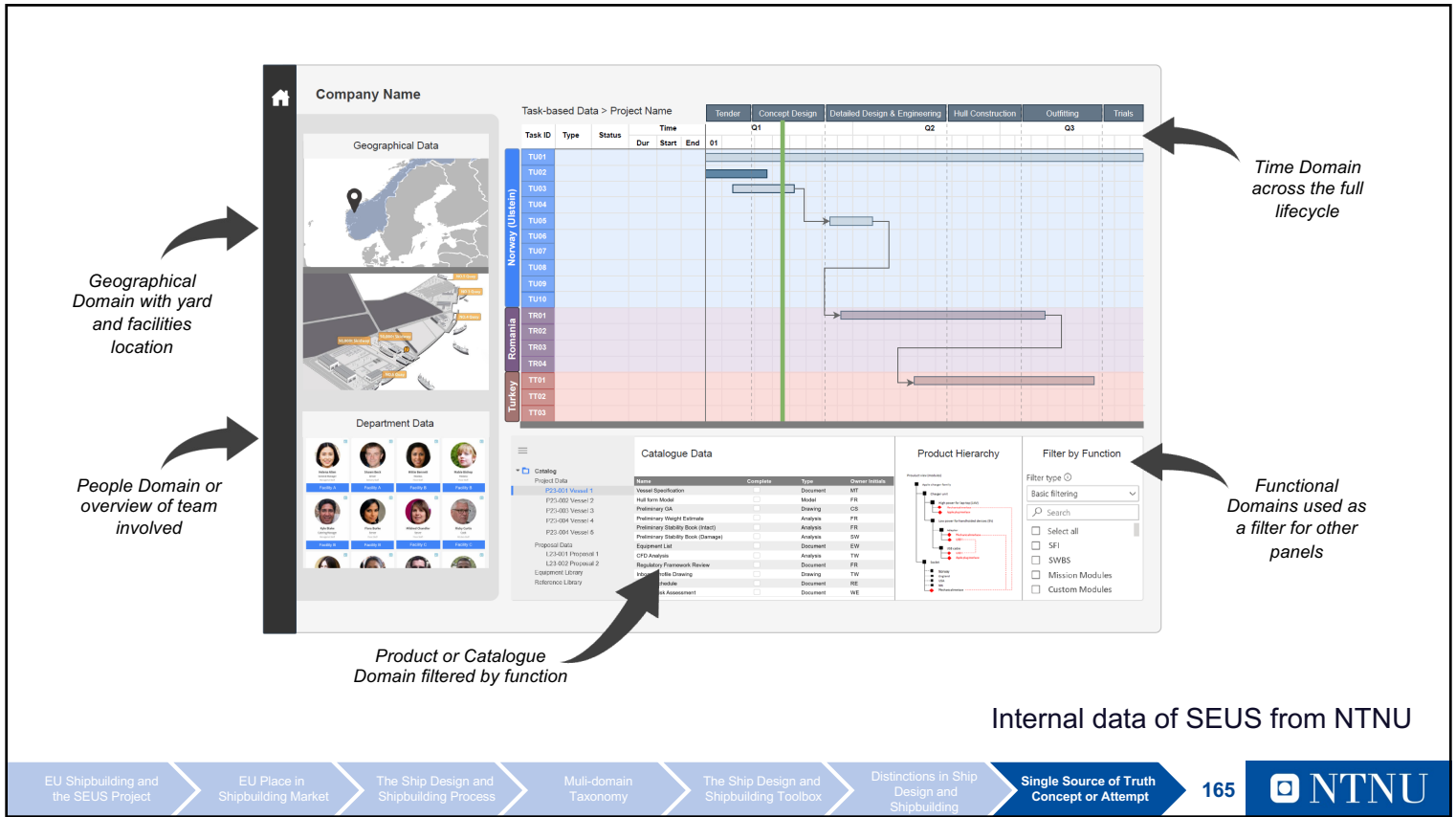
## Ongoing Interview

These surveys are also conducted to determine any immediate feedback or preconceptions with a SSoT solution (inclusive of PLM).

### Solution-focused Questions

- What is your concept of a Single Source of Truth (SSoT) or Product Lifecycle Management (PLM) solution in your line of work?
- What features of an SSoT or PLM solution would be most valuable for in performing the three main activities mentioned earlier?
- Please provide feedback on the following SSoT Interfaces.





## Current & Next Steps

Through the project, outputs have been developed and published by our partners.

Koelman, H. J., Veelo, B. N., Seppälä, L., & Filius, P. (2024). Closing the gap between early and detailed ship design models. *International Marine Design Conference*. <https://doi.org/10.59490/imdc.2024.837> [99]

Proceedings of 11<sup>th</sup> International Marine Design Conference (IMDC-2024)  
June 2-6, 2024  
Amsterdam, the Netherlands

### Closing the Gap between Early and Detailed Ship Design Models

Herbert J. Koelman<sup>1\*</sup>, Bastiaan N. Veelo<sup>1</sup>, Ludmila Seppälä<sup>2</sup> and Paul Filius<sup>2</sup>

#### ABSTRACT

Conventionally, ship design and engineering are segregated activities, carried out with different software packages that thus each have their own place, qualities and tools. And consequently, a different data model. As a report on ongoing work to bridge that gap, this paper first explores existing neutral data models and standards employed or considered in maritime applications and concludes that none of these is directly applicable. It continues with describing the requirements and derived abstract data model of the SEUS project and its design and engineering applications. A graph database is identified as a potentially useful tool for SEUS data modeling, and a hands-on experiment confirms this presumption.

#### KEY WORDS

Ship design methodology; Data models; Digital transition

#### INTRODUCTION

In the ship design process, the transition from early conceptualisation to detailed design marks a critical juncture — a “tipping point” that involves a change of stakeholders. Early design models emphasize the vessel’s fundamental characteristics, naval architectural and functional aspects. Detailed design and production design delve into the intricacies of layout and deal with the generation of production and construction data. This dichotomy in focus leads to disparities in the tools employed and necessitates the alignment of data models.

This paper explores data standards in maritime applications, data models of two particular software systems — PIAS (by SARO) and CADMATIC — and the direction for integrating these models in the SEUS<sup>1</sup> project. SEUS aims at creating a high Technological Readiness Level solution to provide a set of computational tools for shipbuilding, incorporating data flows while the design matures and providing a comprehensive toolset for different stakeholders of the overall shipbuilding process, with access to a single source of true data. However, conventional neutral models or industry standards have not generally demonstrated their suitability for this task, so the research question addressed in this paper is to find a data model for shipbuilding which provides coherence of the data generated along the life cycle. Critical for SEUS are its anticipated impacts — such as a) platform solution for PLM, b) facilitation of digital transformation and c) integration of early design into the overall design process, see Casper et al. (2023) — many of which require software integration between design and engineering. However, it is not the first time in the history of mankind that such an endeavor is undertaken, so in the next section the applicability of existing maritime product data standards is investigated.

weight, length and material, and production data, such as cutting, robot and bending data. All objects have their unique GUID, which are used as a link for all relationships.

The CADMATIC applications use Hull, PAID, Plant Modeller and Piping Isometrics & Spools. All the components, parts, symbols, and design instructions are stored and managed in Library & Project Databases. These databases also include the format control for sheets, listings, and reports. All applications use the same database, ensuring the information remains the same throughout the design project. Access is governed by the COS (CADMATIC Object Storage, see Figure 7) environment, where data is protected from being modified at multiple sites at the same time. Therefore, remote design teams can work in distributed projects using a common model database without conflicts. Projects are split into blocks, general project data, hull line models and 3D models, and these can all be saved to the COS server separately. In PAID, the designer describes the process schematically in 3D format using predefined symbols and metadata information. In Plant Modeller and Piping Isometrics & Spools the process diagram is rebuilt in a 3D format to describe the ship in a realistic way using pipes, fittings, equipment, structural components, etc.

While different applications work in a slightly different way, depending on the discipline they serve, the overall project data is consolidated in the COS database. CADMATIC represents so called “user-driven” CAD solution, which focuses primarily on the shipbuilding nature of the designer’s work, see Duib et al. (2017). Each application has their own API to serve the needs of particular integrations for design disciplines, while COS Web API serves the needs of integration with overall project data.

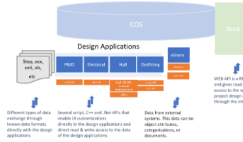


Figure 7: CADMATIC Object Storage structure.

#### A sketch of the SEUS service warehouse

As a learned lesson, it is worth reflecting on a prior CADMATIC – PIAS interface, see Koelman et al. (2015), which comprised a) direct communication over TCP/IP instead of a shared database, b) data synchronization on demand, rather than continuously, and c) exchange of high-level data entities, based on STEP semantics, which means that in essence the deeper data representations were not shared. For example, both systems had a notion of deck, which was shared, while the underlying representations differed quite radically. As such, that software collaboration was impressive to see, with two windows open, showing the same model in the two distinct applications, with one press of a button the changes from one was transferred to the other. Nevertheless, the direct TCP/IP communication had one drawback: the lack of a central permanent storage. If one of the applications was not connected, the job/revision creation from the other stopped. This conclusion, combined with the other analyses and experiments in this paper, led to an envisioned SEUS warehouse with the following functions and services:

1. Storage of data and their relationships are extendable, offering varying Levels of Detail, and multiple facets (i.e. the entities can be part of multiple taxonomies, each of a different kind and with a different purpose).
2. The data separation based on the maritime STEP application protocols, extended where required.
3. Should this come down to a dictionary, then preferably some integrated documentation system for human use is required.
4. There is many communication by API or PRC with this storage system, including systems of varying types, such as high-level programming languages and scripting tools.
5. It is enabled with a set of system-wide services, among which there is conversion of data representations.
6. Control of access of the data is possible.

To underline that this is not limited to data, this is called a service warehouse, in analogy with a physical warehouse, where services are also provided, with or around the goods.

## Current & Next Steps

Through the project, outputs have been developed and published by our partners.

Seppälä, L. (2024). Industry 5.0: Transforming ship design through human-centered approach. *International Marine Design Conference*. <https://doi.org/10.59490/imdc.2024.865> [100]

Proceedings of 11<sup>th</sup> International Marine Design Conference (IMDC-2024)  
June 2-6, 2024  
Amsterdam, the Netherlands

### Industry 5.0: Transforming ship design through human-centered approach

Ludmila Seppälä<sup>1\*</sup>

#### ABSTRACT

Industry 5.0 heralds a paradigm shift by reinstating the significance of human centrality alongside technology. Incorporating human collaboration into the design methodology aligns with general project management methodology and addresses the imperative of facilitating sustainable goals in the industry. Focusing on human skills and aspirations offers a viable path to expedite the adoption of new technology into the mainstream, aligning with the evolving needs of the shipbuilding industry and green targets of society development. The article delves into the implications of the Shipbuilding 5.0 paradigm to design process and methodology, the potential changes it brings, and the potential benefits it can offer to the evolution of the shipbuilding industry.

#### KEYWORDS

Shipbuilding 5.0; Human aspects of technology; Digital transformation; Design methodology

#### INTRODUCTION

The ship design process is often perceived as a primary engineering discipline focused on functionality. There are numerous methodologies and approaches to managing and organizing this process and many forums where such topics are discussed. A recently introduced concept to the shipbuilding world is Industry 5.0. Initially developed by the EU (European Union Publications, 2021), it takes the previous idea of Industry 4.0 to the next level. The levels of the Industrial Revolution are conceptual simplifications capturing the core changes in the social-technology landscapes and related processes understanding. These levels should not be interpreted as an assessment of the technology use, readiness, or advancement in digitalization, as these only indicate the industry’s transformation stage and a conceptual framework.

Changes described in Industry 5.0 can be reflected in the evolution of the shipbuilding industry and ship design process. This article explores what changes in ship design can be expected in the context of Industry 5.0. It starts by providing an overview of the Industrial Revolution concepts focusing on ship design and shipbuilding, identifying impact areas, examining each area in detail, and offering a framework approach for considering the human-centricity perspective.

the desire for stronger vessels or the establishment of longer sailing due to more reliable ships. Later, CAE/CAD/CAM technology enabled more complex and opened the doors to robotized production processes. This process is still ongoing; however, hardly any ship design is performed without the involvement of IT technology. Now, we witness the next key leap forward with data management systems, advanced simulation, and a human-centric finding its space in the IT technology world of shipbuilding. The latest stage of evolution, Shipbuilding 5.0, is expected to focus on placing human needs and capabilities at the heart of intelligent IT to take cyber-physical systems to the next level.

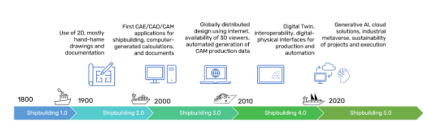


Figure 1: Evolution of concepts towards Industry/Shipbuilding 5.0 and main driving forces behind the concept levels and ship design technology.

For the ship design process, these steps can be described as a change from manually made design to technology-creating design based on human input. Only 30 years ago, it was a mainstream practice to do calculations and prepare all documentation using pen and paper or a calculating machine at best. Some 20 years ago, the first applications for engineering calculations were employed for ship design. At about the same time, the first CAD application provided the possibility to create a digital model and 3D model to enhance engineering decisions and generate more accurate output. There are technical possibilities to present the design model in Virtual Reality (VR), use simulation to assess hull forms and propulsion alternatives, and involve any expert anywhere in the world in the design process. These are undeniable advancements of the change that affects the ship design process due to technology and societal evolution. Industry 4.0 emphasizes a connection between digital models and physical products, while Industry 5.0 adds a human-digital-physical layer of complexity. Considering the latest stage, Shipbuilding 5.0, expectations are high with generative AI applications popping up in all areas, the industrial narrative making its first steps into the industry, and co-bots and robots being employed in many shipyards for various tasks. What makes it unique in its overall focus on sustainability and resilience. It can be expected that the ship design process will be affected by these changes, and the following sections outline some of them.

#### AREAS OF SHIP DESIGN WHERE HUMAN-CENTRIC APPROACH CAN INFLECT CHANGES

The primary goal of shipbuilding lies in large-scale transportation, with various goals in river, sea, and ocean exploration. There are numerous purposes for worldwide transportation and human activities on and underwater. These goals are often substituted in ship design with derived imperatives, such as “delivering value for owners and operators” and ensuring the safety of operations. We must return to the origin and address the initial question: why does society need waterborne transportation and exploration of the rivers, sea, and oceans? While the response to these questions might be obvious, the presentation of the question in this form opens the core of the Industry 5.0 concept, placing human intentions and interests at the core of all processes. Focusing on the core of the initial reason provides a key to evaluating how to fulfill the request. This view, the discussion is taken from the context of shareholders, such as the owner or operator perspective, into a more comprehensive background of stakeholders, such as society, regional differences in communities, and people who will operate and use the vessels. This is a primary shift towards human-centricity, which should be performed before functional requirements.

The shipbuilding industry is different from other transportation industries. There are many explanations for this, ranging from the narrow specific expertise required for naval architecture to the complexity of projects closer in scale to offshore production facilities, such as power plants. Additional differences can be found in the methodology approach: product versus project. While most similar industries refer to the end product as a product and hence apply product design and management

## Current & Next Steps

Through the project, outputs have been developed and published by our partners.

Seppälä, L. (2023). Integrated Shipbuilding Data Management. *Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT)*. <https://www.cadmatic.com/en/resources/articles/integrated-shipbuilding-data-management/> [101]

### Integrated Shipbuilding Data Management

Posted on August 08, 2023

This paper was presented for the first time at the annual Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT) held in Drübeck, Germany, from 23-25 May 2023.

Author: Ludmila Seppälä

#### 1. Introduction

Ship design and building require naval architecture, engineering, and technology knowledge. These areas are essential for defining the functionality of future floating structures and receive the most academic and computational attention. For a typical commercial vessel construction project, detailed engineering requires the management of up to 5 million construction components. Shipbuilding projects for marine structures typically last between one and five years and demand extensive process management data. This includes managing downstream and upstream shipbuilding data, materials, and personnel and data management for the entire engineering and production process. Unfortunately, these aspects are frequently neglected in research, but they present opportunities for shipbuilders to gain a competitive edge and benefit from digital transformation.

This paper focuses on integrated data management throughout a vessel's design and construction process, including extensive change management and overall management of all related data, including 3D and 2D designs, documentation, and bills of materials. The topic relates digital solutions for ship design and data

management. From a data perspective, the design process is associated with a vast quantity of diverse data types, including 3D models, calculations, drawings, and specifications, among others. A PDM (Product Data Management) system is commonly used to manage and control this information. Such systems, prevalent in other industries, have only recently been implemented in shipbuilding. The final layer is process management, which reflects how the shipyard or design office organizes and manages activities – a design for the organization, workflows, project management, etc. The interconnection of these three layers is where digital tools can significantly optimize the time and costs of the overall project. The shipbuilding industry was focused on design processes and tools for a long time, disregarding the other aspects. Data storage and management were partially included in the scope of intent-driven design tools, and process management is often overlooked as a purely business or organization management discipline.

This paper provides a generic consideration for the three layers discussed, humbly acknowledging that each shipyard or ship design organization works uniquely. This way of working often encapsulates a competitive advantage or trade secret. The primary goal of this paper is to find an underlying model that can help describe the overall process and pinpoint possibilities to adapt existing tools, learn from other industries, or improve software tools.

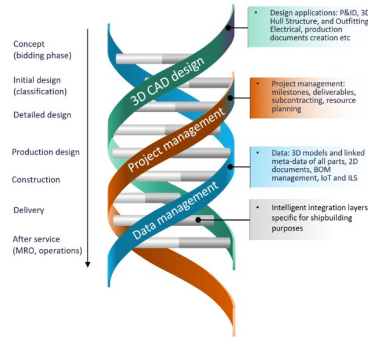


Fig 1: Aligned processes along the shipbuilding lifecycle: Design, Project Management, and Data

EU Shipbuilding and the SEUS Project

EU Place in Shipbuilding Market

The Ship Design and Shipbuilding Process

Multi-domain Taxonomy

The Ship Design and Shipbuilding Toolbox

Distinctions in Ship Design and Shipbuilding

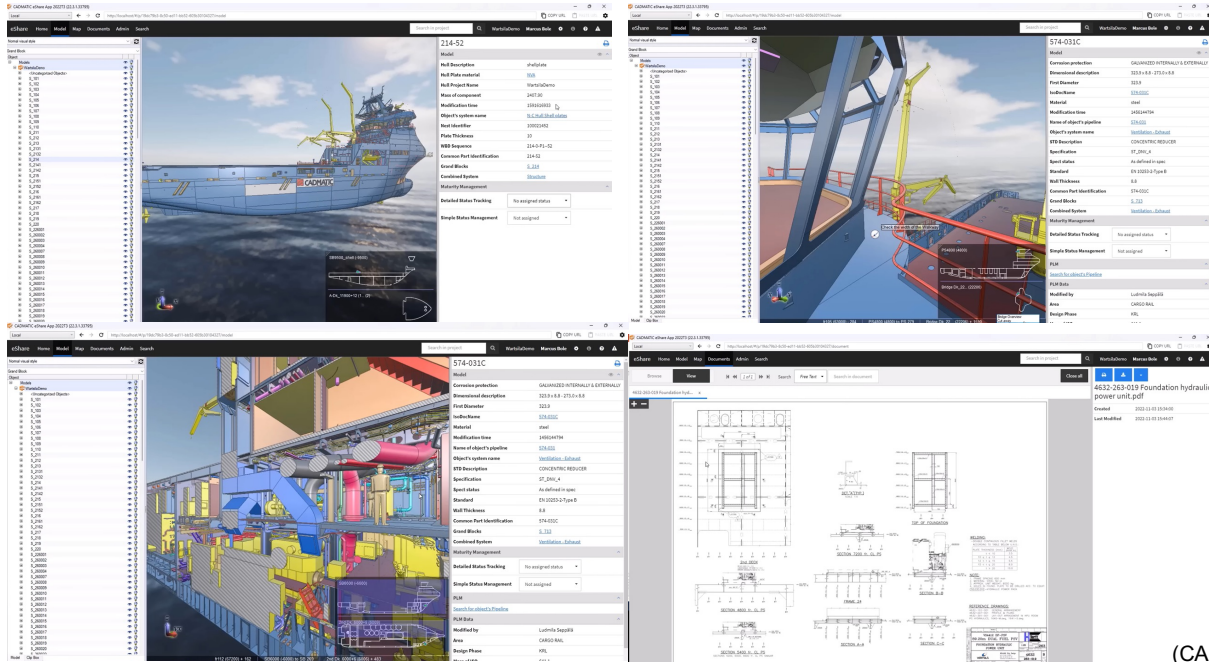
Single Source of Truth Concept or Attempt

169

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CADMATIC's eShare for linking, visualization, and sharing design, production, and operational ship information



(CADMATIC, 2023 [97])

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## Conclusion

Since the 1980s, the potential of incorporating computer-aided design and computational tools into shipbuilding has been acknowledged. With the realization of digital twins, digital threads, and PLM – how far off are we from realizing these forecasts?

It is the view of the author, from the research reported in this paper, that ship design is a far from simple process and furthermore the momentum behind developments in preliminary **CASD** to simplify the initial design 'synthesis' is no longer necessary or desirable. The more sophisticated design description, provided by an integrated synthesis, rightly makes the designer consciously address, as early as possible, many of the less **tangible** design issues. With the developments underway in **CAD**, Artificial Intelligence and Expert Systems<sup>(33)</sup> the ship designer, along with the other designers 'on the grand scale', must mould the application to design of computer methods to provide an open, responsive and 'softer' approach to **CAD**.

**\*digital tools**

(Andrews, 1986 [63])

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