SEUS
Smart European Shipbuilding

Funded by the European Union

Best Practices in European Ship Design and Shipbuilding

Work Package 1 Deliverable

Henrique Gaspar (henrique.gaspar@ntnu.no)
Janica Echavez (janica.echavez@ntnu.no)

January 2024, Version 2
Updated from November 2023, Version 1

Norwegian Universitas of Science and Technology

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 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."*

- At this stage (January 2024), the authors expect that the SEUS partners can use this as a reference and common ground for our understanding so far.
- This is a work in progress. We expect to get feedback from the partners by mid-February, with comments on points of improvement as well as gaps.

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
6. Distinctions in Ship Design and Shipbuilding
7. Single Source of Truth Concept or Attempt

Best Practices on Ship Design and Shipbuilding: Outline

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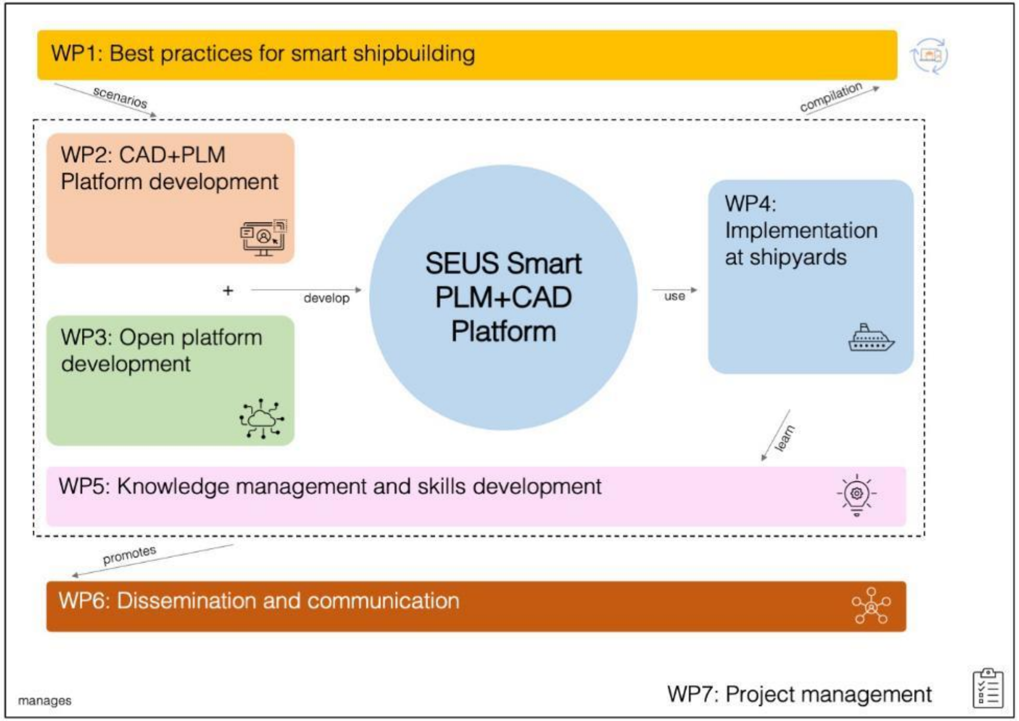
This document is a live draft for the WP1: Best Practice for Smart Shipbuilding and is intended to be a compilation of literature regarding ship design & shipbuilding processes and maritime digitalization.



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

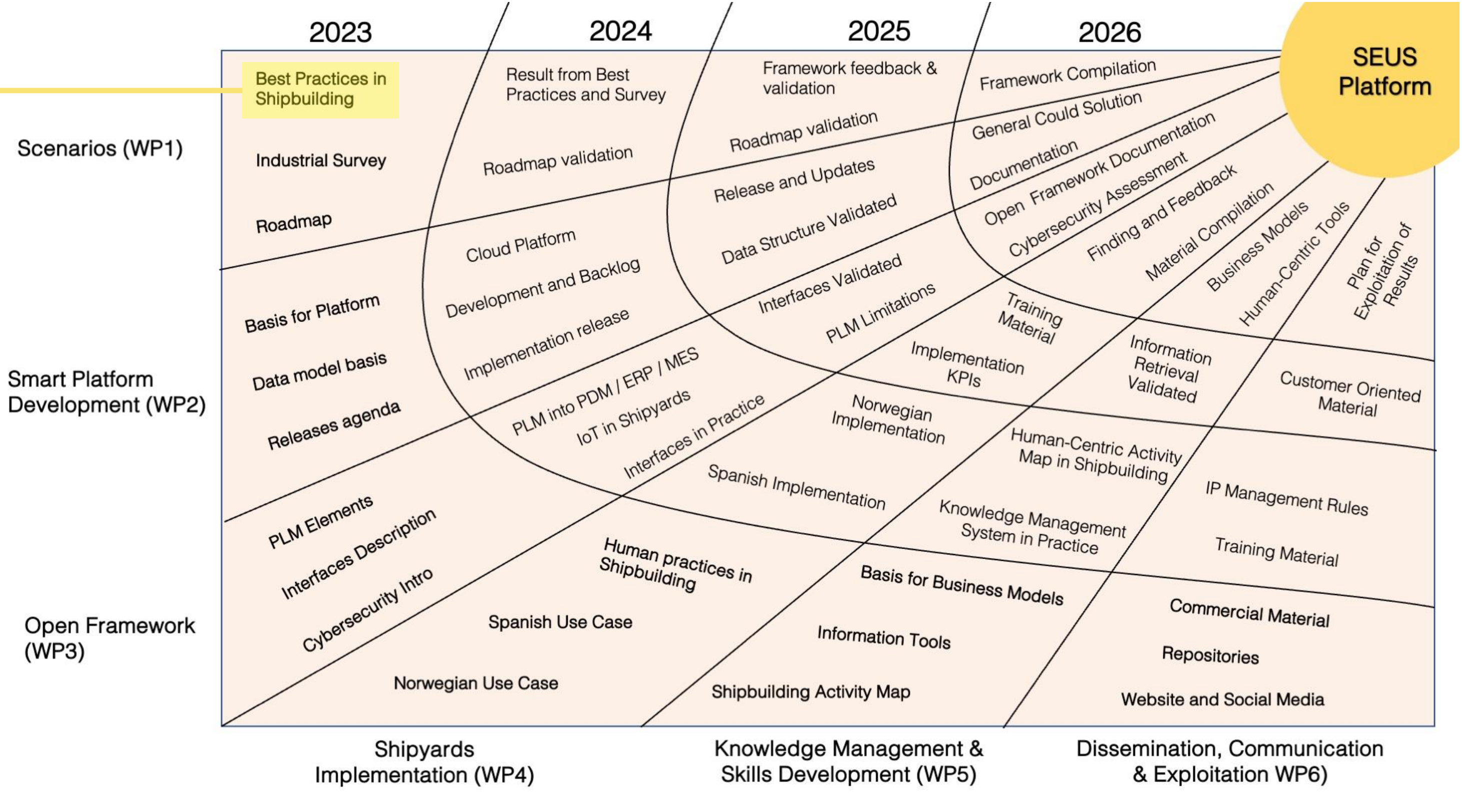
WP3: Open Platform Development
Responsible: CONTACT

WP5: Knowledge Management & Skills Development
Responsible: UTU

Additional feedback on sections that require modification is greatly appreciated.

SEUS Sun Diagram – Visual Roadmap

This work in relation with other WPs towards the SEUS Goal



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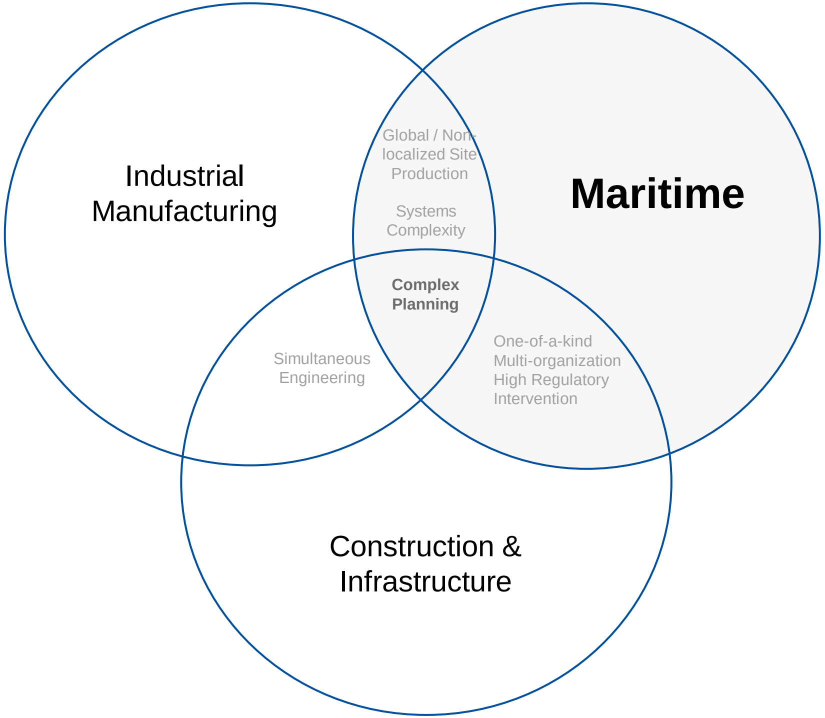
The Maritime Industry is a peculiar and one-of-a-kind industry.

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.

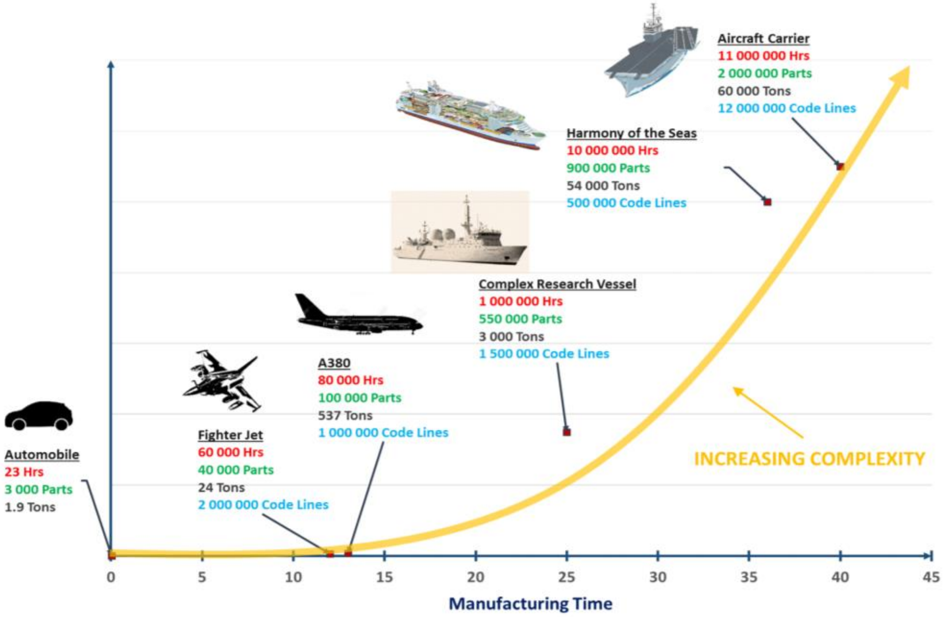


Four peculiarities of the industry, adopted from Emblesmvåg (2014):

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.

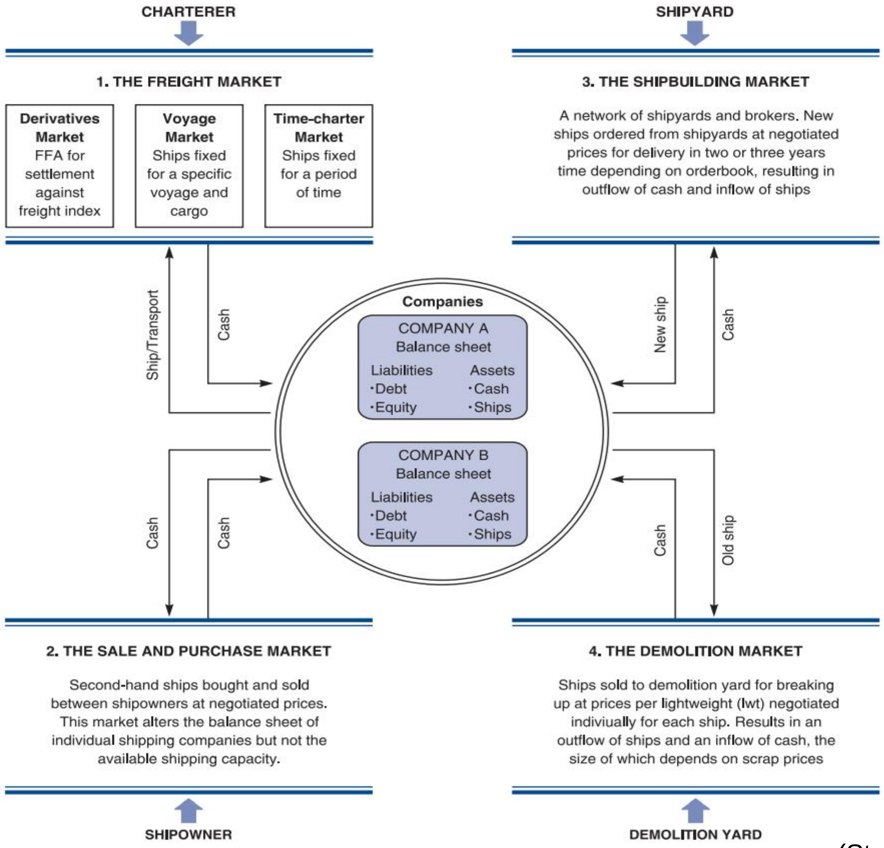
A 537-ton Airbus A380 comprises four million individual parts from 1,500 companies from multiple countries globally (Slutsken, 2018). On the other hand, a USS NIMITZ Aircraft Carrier has about a billion parts.



https://www.cesa.eu/the-industry (Adopted from Cottrell, et al. (2009))

USS Nimitz Class
(Naval-Technology)

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



(Stopford, 2007)

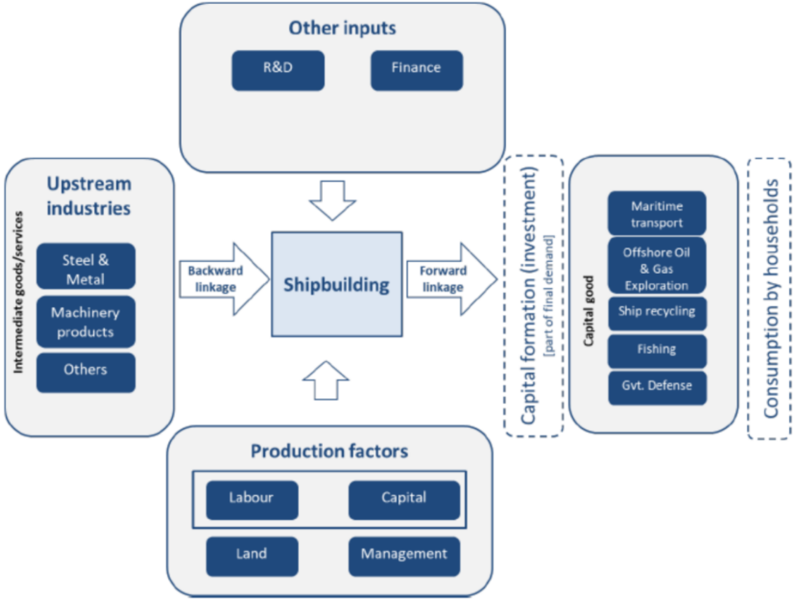
Of these markets, **the ship design and shipbuilding (SD&SB) market** is the most **capital-intensive** to disrupt.

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 (Hyudai, Mitsui, Kawasaki, etc.), oil companies, offshore contractors, and other entrepreneurial shipowners.



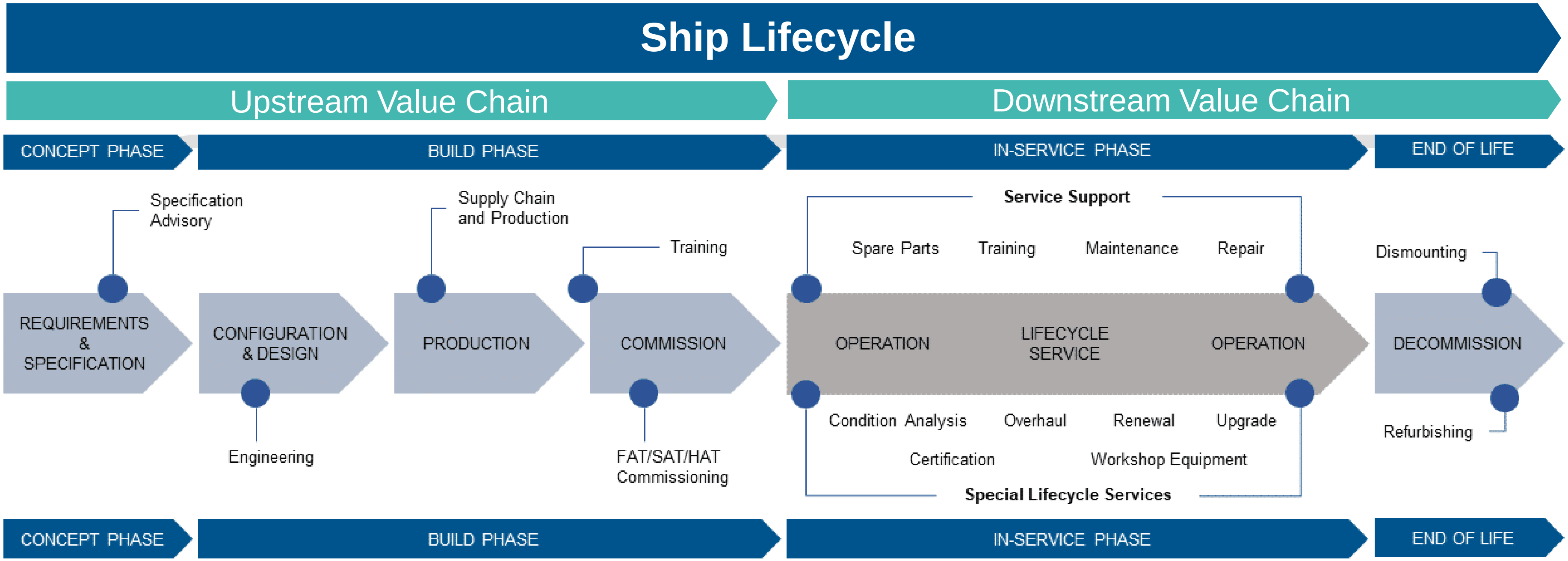
(OECD, 2023)

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.

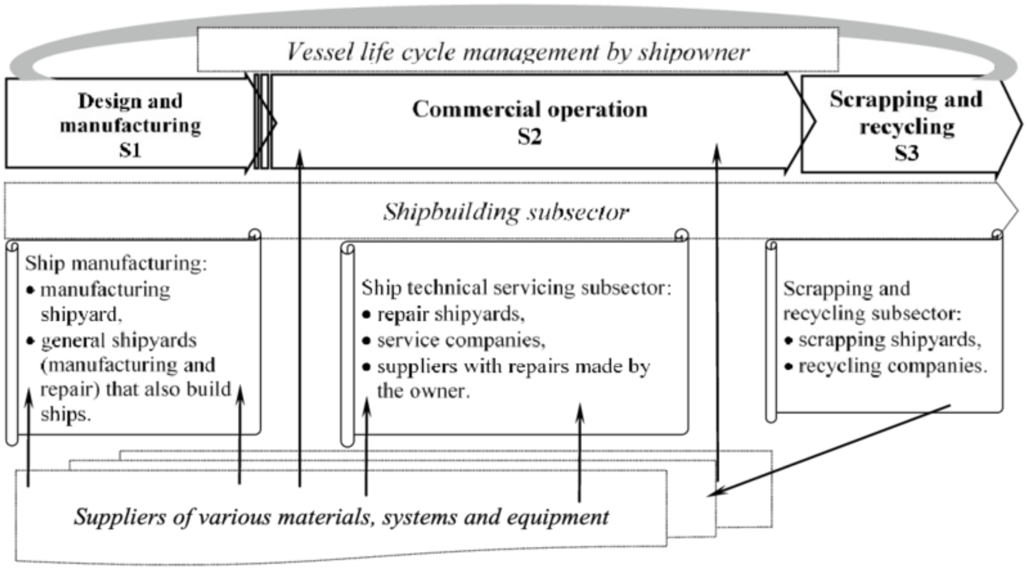
Companies support the design, build, operations, and decommissioning of a ship throughout the entire vessel's lifecycle.



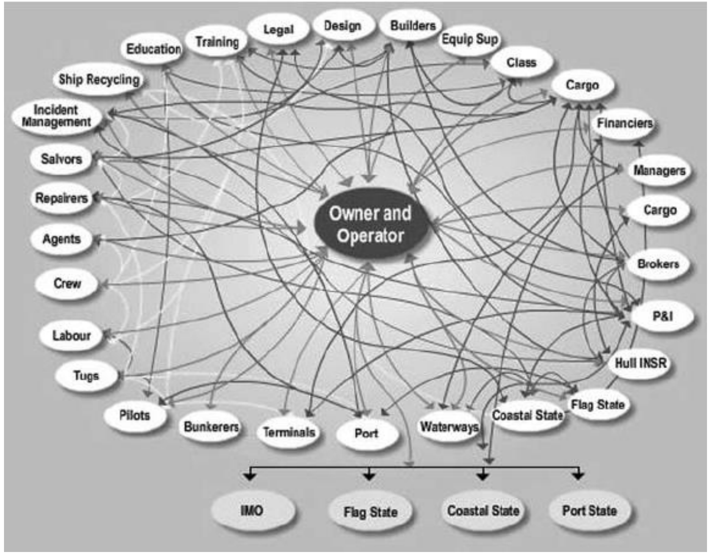
https://www.gabler-naval.com/lifecycle/

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.



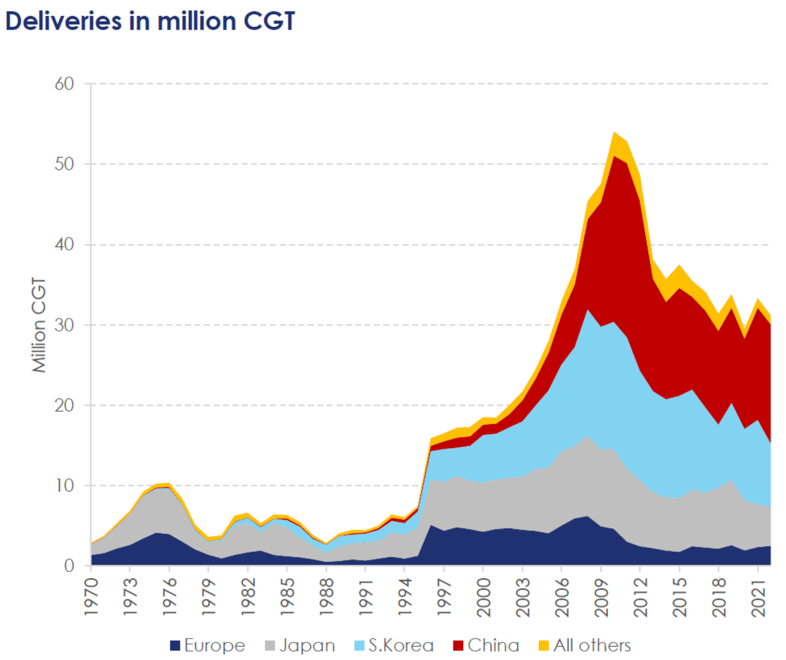
(Montwiłł, et al., 2018)

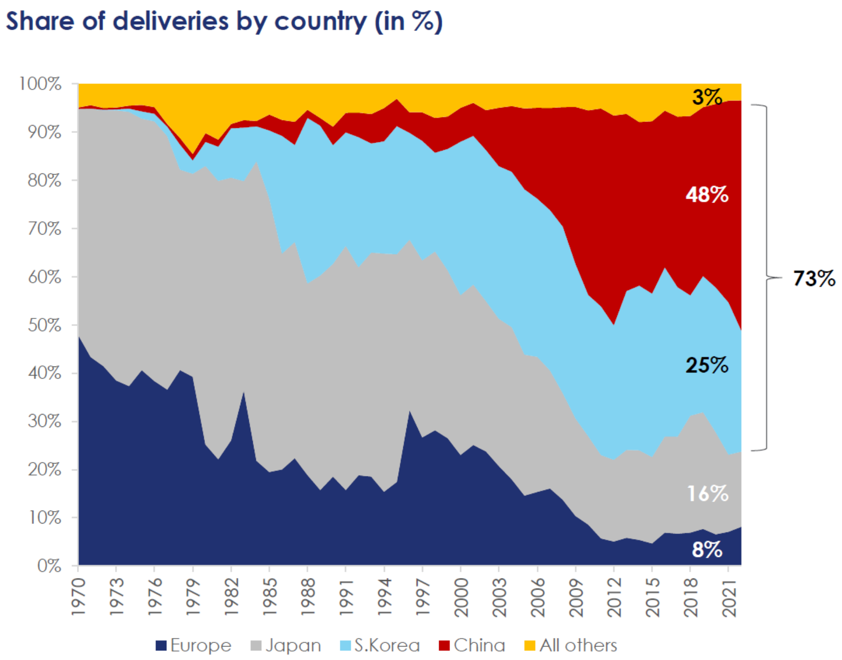


(Koçak, 2015), Adopted from (Maritime Industry Foundation, 2013)

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%.



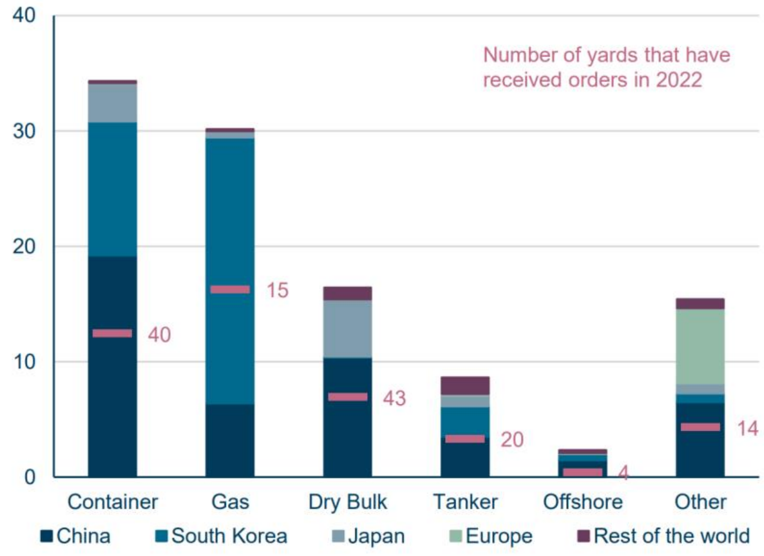


(Clarksons, 2023)

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)

Table 2.2 Deliveries of newbuilt vessels by type and building country, thousands of gross tons, 2022

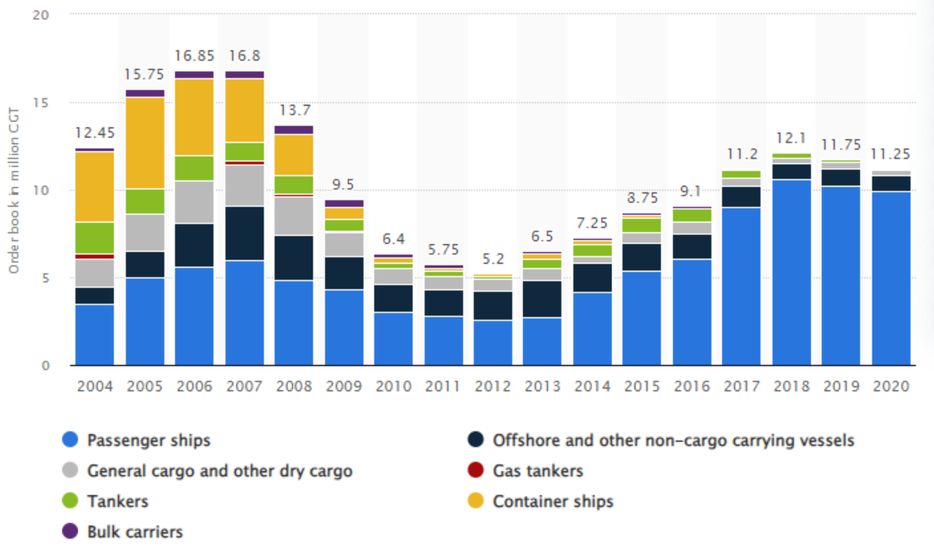
	China	Japan	Republic of Korea	Philippines	Viet Nam	Europe	Rest of the world	World total	Percentage share
Bulk Carriers	11 233	5 360	443	344	98			17 477	31.4
Oil Tankers	4 203	1 745	8 294		318	157	10	14 727	26.5
Containerships	5 361	1 487	3 263	50			44	10 205	18.4
Gas Carriers	899	268	3'665			7		4 838	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
Total	**25 895**	**9 585**	**16 254**	**396**	**444**	**2 464**	**542**	**55 580**	**100.0**
Percentage share	**46.6**	**17.2**	**29.2**	**0.7**	**0.8**	**4.4**	**1.0**	**100.0**	

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

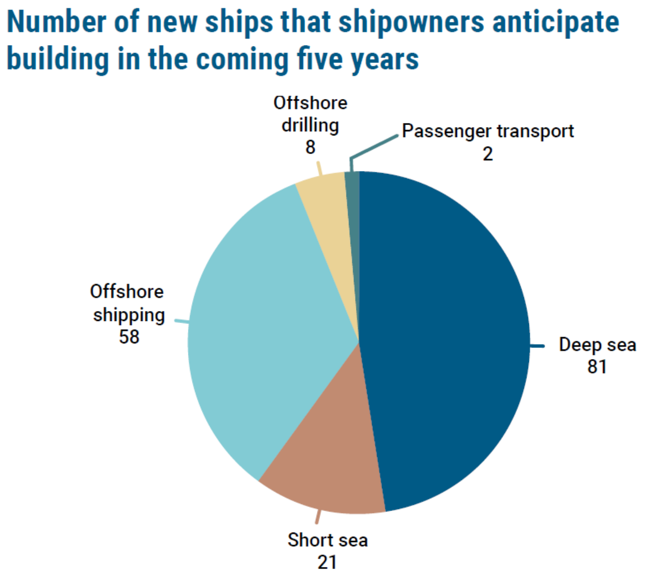
Notes: Propelled seagoing merchant vessels of 100 GT and above. See also http://stats.unctad.org/shipbuilding.

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.



(Statista, 2023)



(Norwegian Shipowners' Association, 2022)

Highly specialized vessels and complex NCC ships include:

Passenger Ship

Fishing Vessels

Dredgers

Platform Supply Vessel

Seismic Vessel

Wind Farm
Installation Vessels

Source (Top Left, clockwise): Hurtigruten (vard.com), Selvåg Senior (Skipsteknisk), Spartacus (Royal IHC), Skandi Flora (DOF), Polarcus (Ulstein), Van Oord

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).

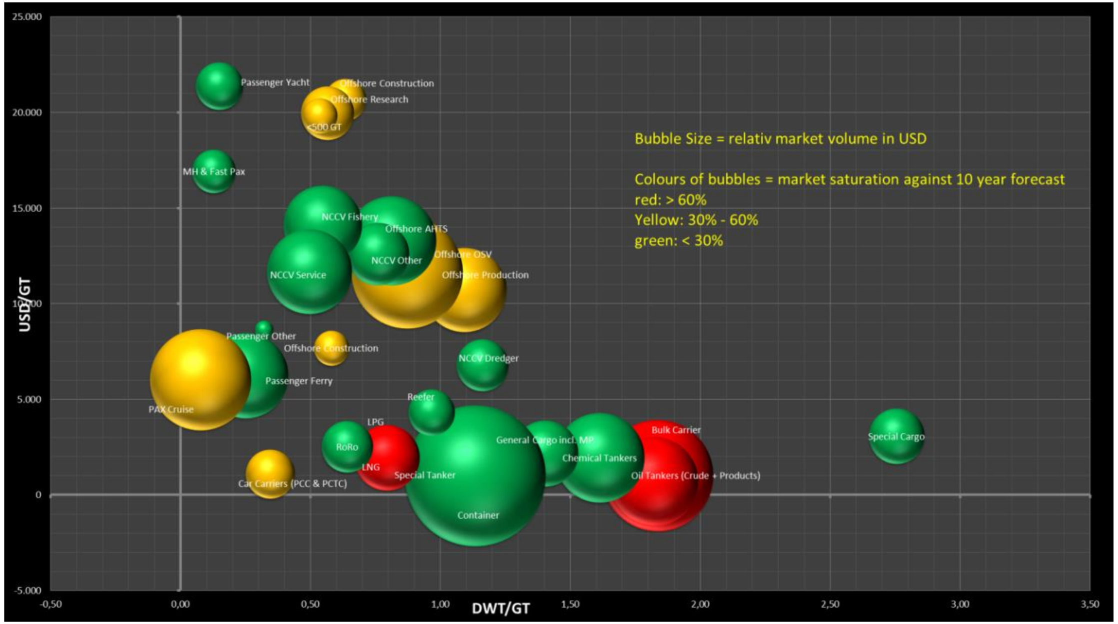


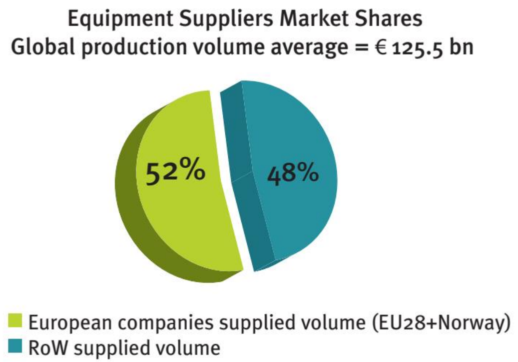
Figure 24: Shipbuilding market forecast 2016-2025
[Source: BALance TC calculations]

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.



(OECD, 2023) and (SEA Europe 2017), Adopted from (BALance Technology Consulting (2017))

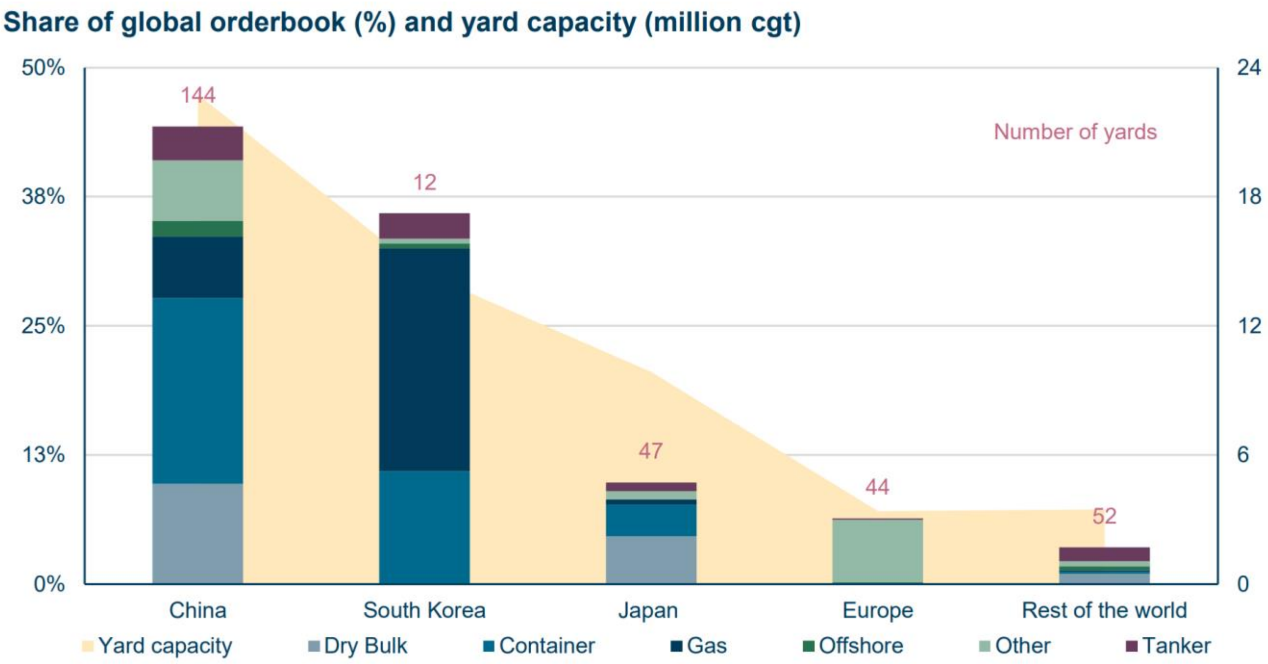
European shipyards have adapted to new demands by offshoring the construction of certain ship parts to keep costs low, allowing them to focus on complex outfitting and repairs.

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

(Trusted Docks, 2023)

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.**



(Danish Ship Finance, 2023)

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.

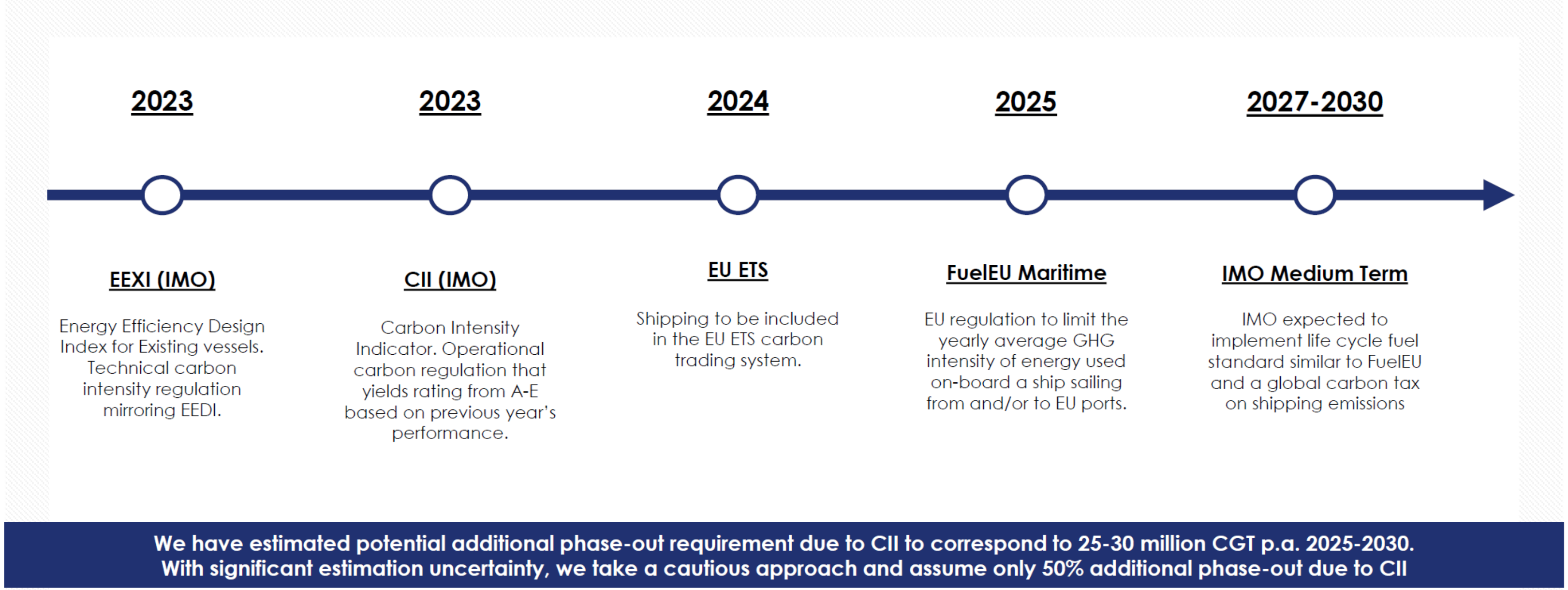
Geopolitics and Trade Dynamics	Environment	Industry 4.0 Trends
US-China Trade Tensions affecting tariffs Race for Arctic Resources Tension in Maritime Chokepoints Structural shifts in globalization patterns	Accelerating environmental and regulatory agenda Melting of Polar Caps Rising Sea Level Ocean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

Adopted from (UNCTAD, 2019)

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.

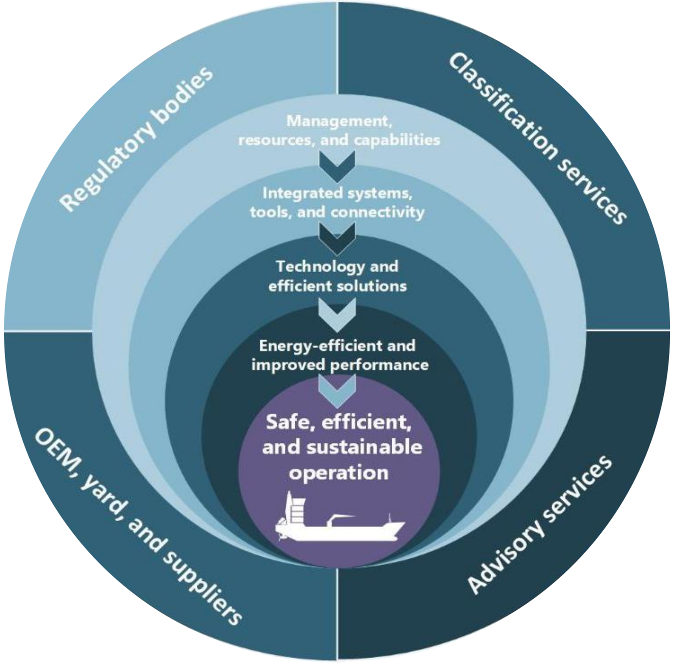
Environmental Regulations:



(Clarksons, 2023)

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:

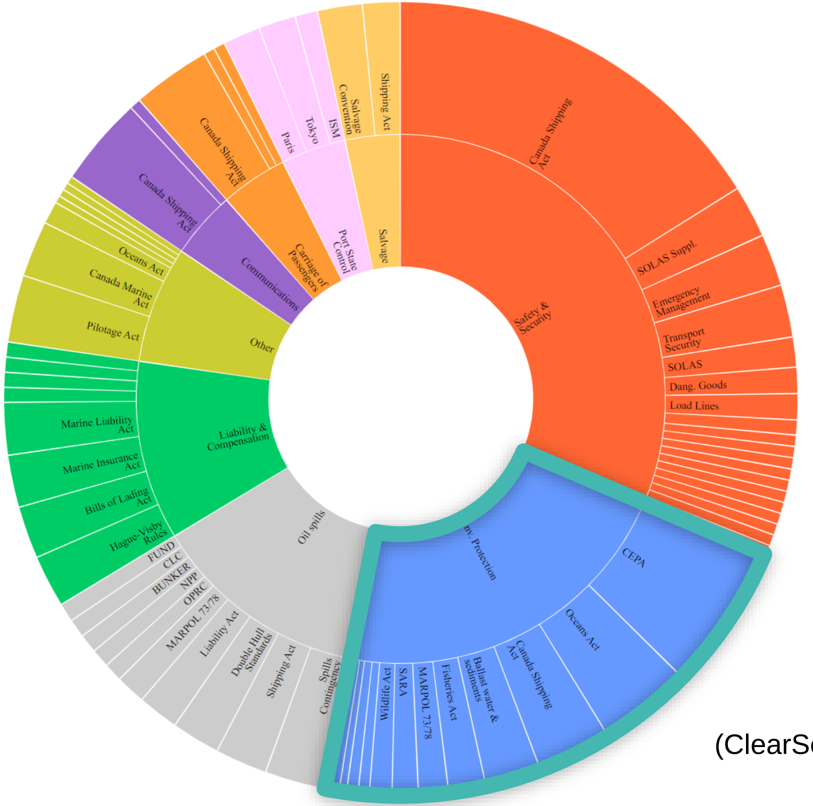
These shifting maritime laws and regulations mean design thresholds related to safety and the environment change year after year.

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)

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

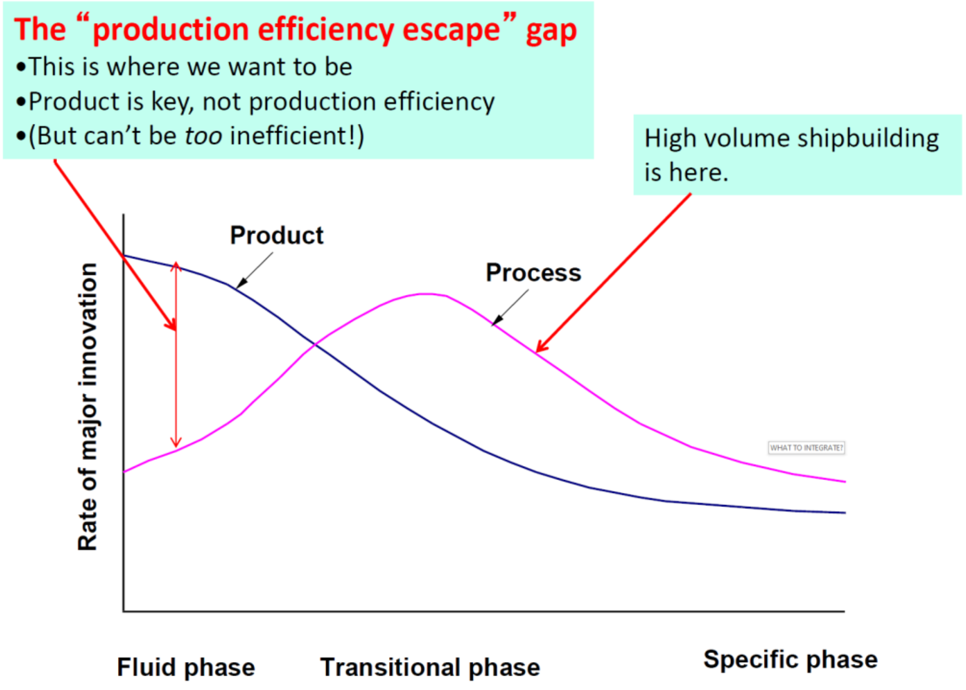
- Industry is designed to maximize **custom and specialized ships** (from OEMs to ship-type investments) which requires a high degree of systems integration in both design and construction
- Extreme **multi-organization** with yards abroad requires high collaboration and robust data security
- **Limitations 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
• Level of innovation • Innovative SMEs and strong position of marine equipment industry • Strong linkages between yards and Marine equipment • Efficiency • Specialisation in niche markets • Spillovers between defence and commercial segments	• Cost levels • Access to skilled labour • Potential difficulties in knowledge protection (especially among SMEs) • Fragmented government responses
Opportunities	**Threats**
• New segments, continuous innovation • Greening of shipbuilding industry • Existing transport policies (greening of transport, increased transport quality) • Enhanced requirements regarding shipping standards	• Demand shift from EU to Asian buyers • Strengthening of Asian maritime cluster • Increasing development of marine equipment industry • Competitors moving up the ladder • SME's not surviving the crisis • Flexible and swift competitor's governments to support their industry • Critical mass required to maintain/refresh high skilled workforce. Europe may be too small compared to competitors. Ageing workforce • Price competition in light of economic crisis

(Thamby, 2023)

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

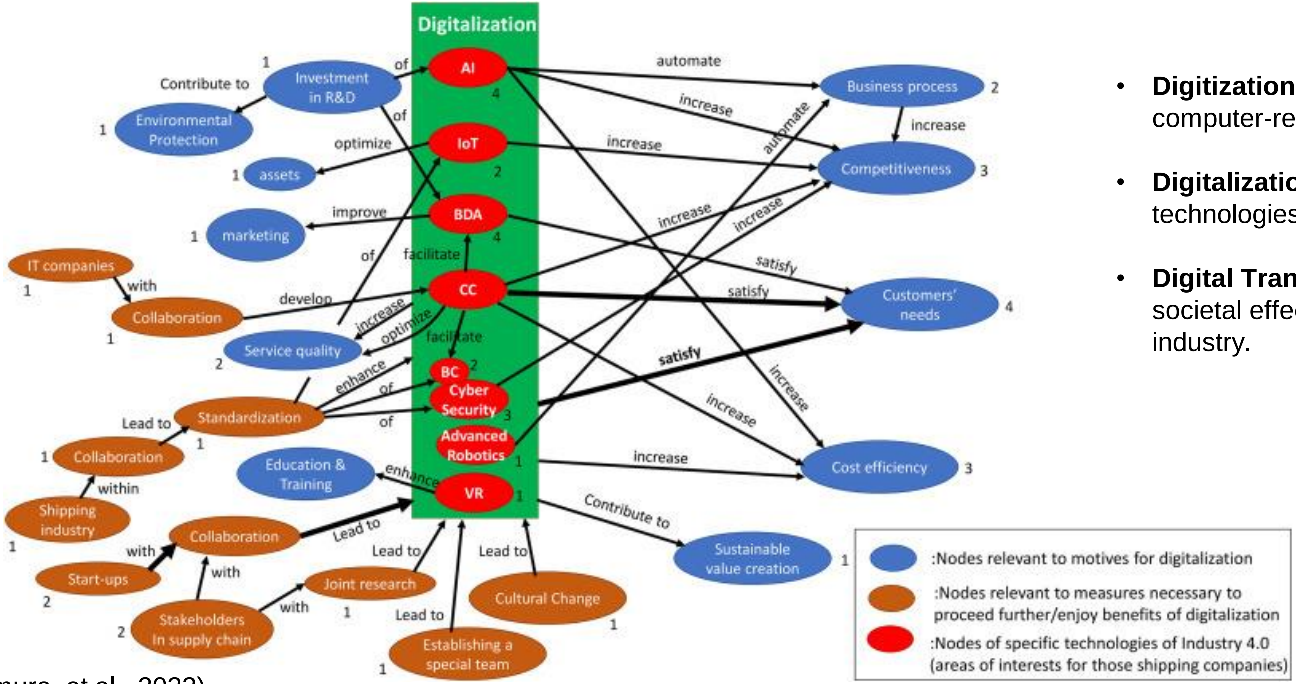
As the Production Efficiency curve suggests, trade-offs between product innovation and process efficiency exist. Is there an optimal set of conditions that can enable high product innovation and process efficiency for the European market?



(Koenig, 2019)

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.

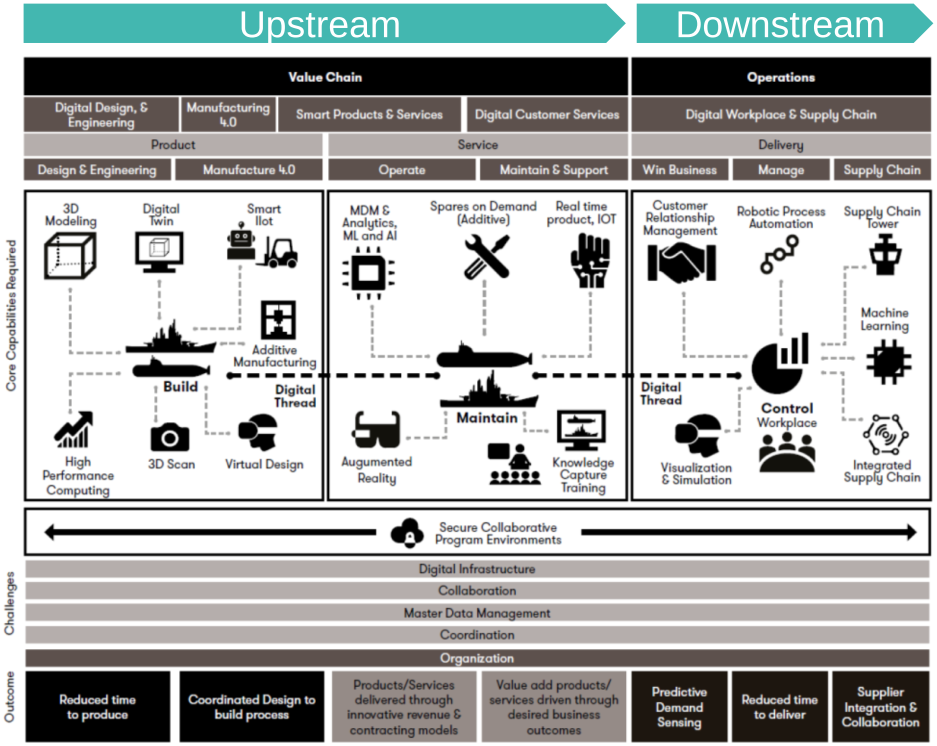


(Ichimura, et al., 2022)

- **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

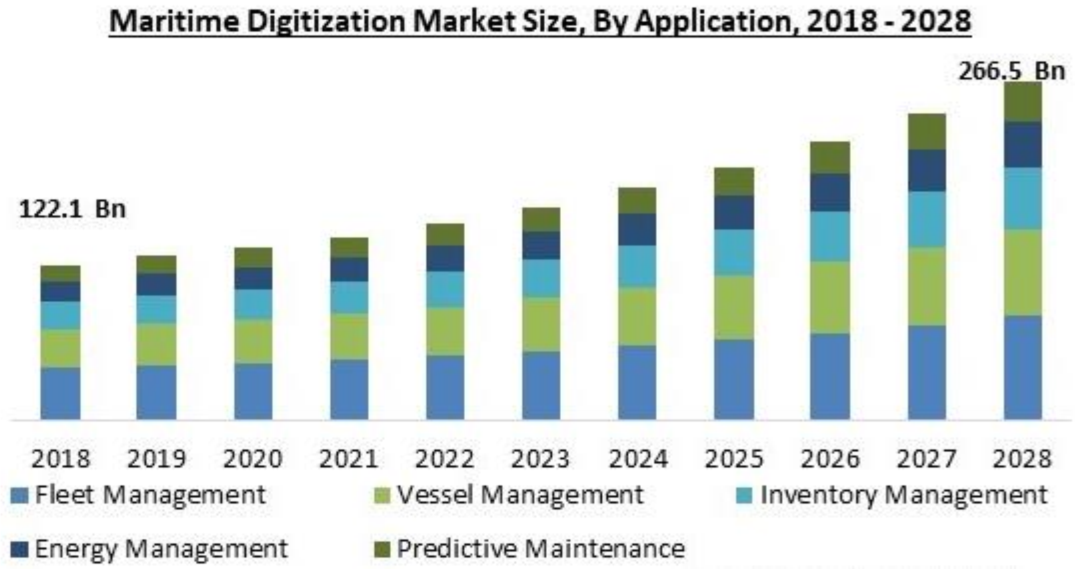
Studies and assessments show that there are multiple opportunities for process improvement with digitalization across the ship's lifecycle, from ship design to operations.



(Spoehr, et al., 2021), Adopted from Ash (2018)

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.



(KBVResearch, 2023)

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

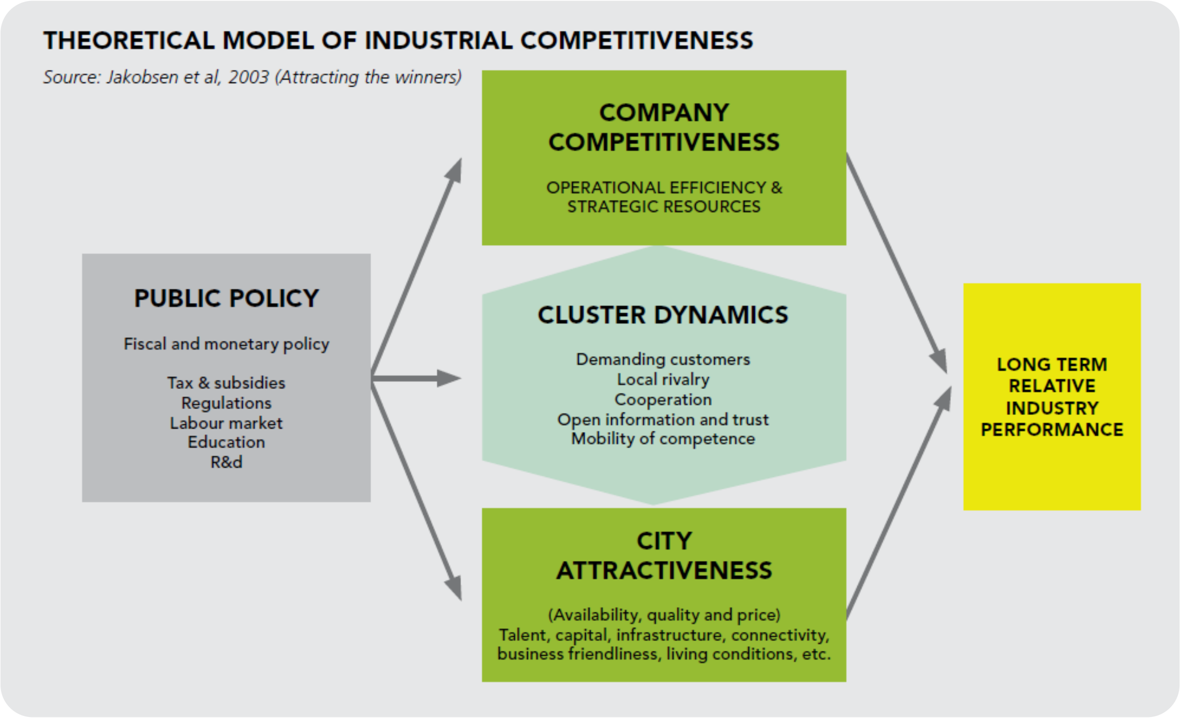
Up to 20% of fuel savings can be attained with better vessel utilization and alternative route planning.

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

LOGISTICS AND DIGITALIZATION	HYDRODYNAMICS	MACHINERY	ENERGY	AFTER-TREATMENT
Speed reduction Vessel utilization Vessel size Alternative routes	Hull coating Hull-form optimization Air lubrication Cleaning	Machinery efficiency improvements Waste-heat recovery Engine de-rating Battery hybridization Fuel cells	LNG, LPG Biofuels Electrification Methanol Ammonia Hydrogen Wind power Nuclear	Carbon capture and storage
>20%	5%-15%	5%-20%	0%-100%	0%-90%

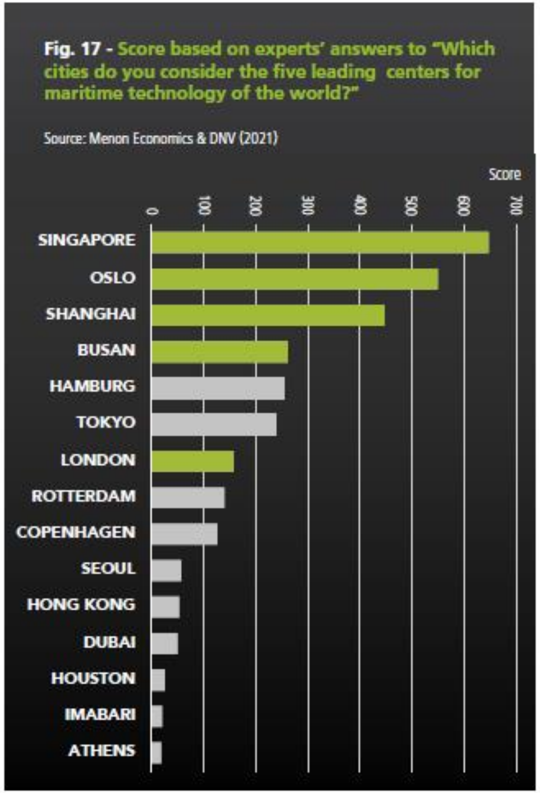
(DNV, 2023)

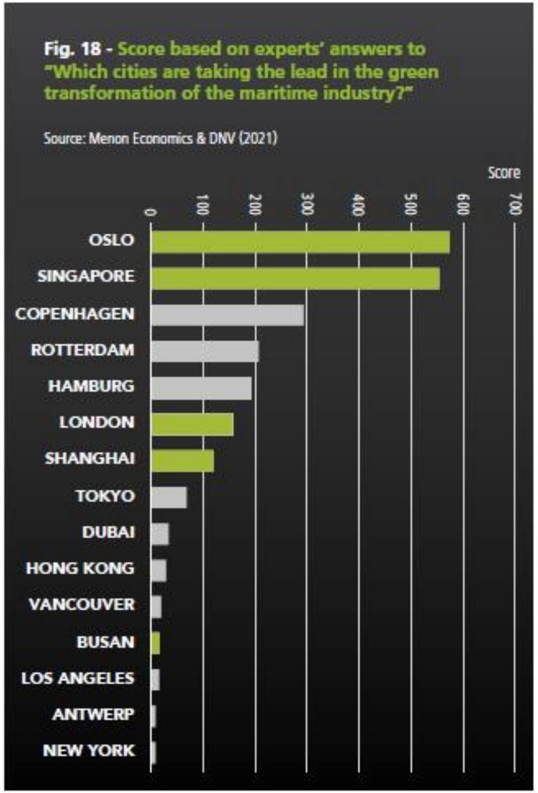
Why clusters are important? Clusters are a group of industries that are directly and indirectly tied to an industry within a geographical area. These clusters help to drive and facilitate innovation.

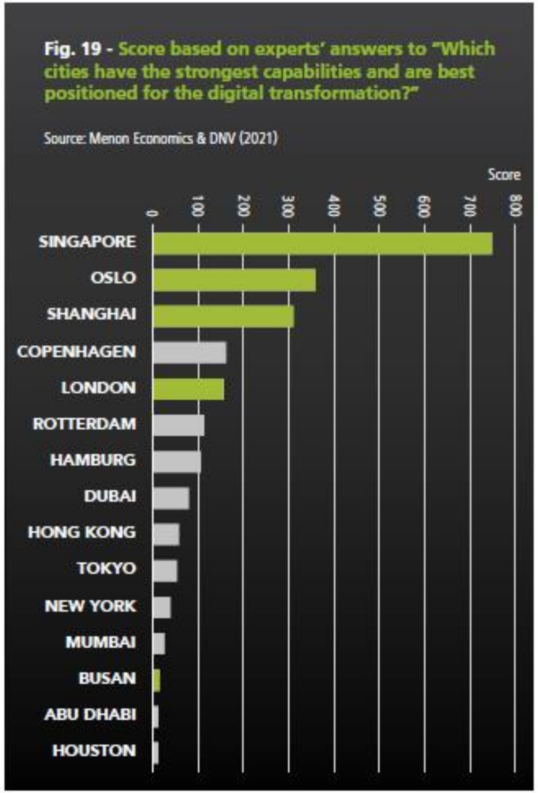


(Menon Economics, 2022)

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







(Menon Economics, 2022)

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

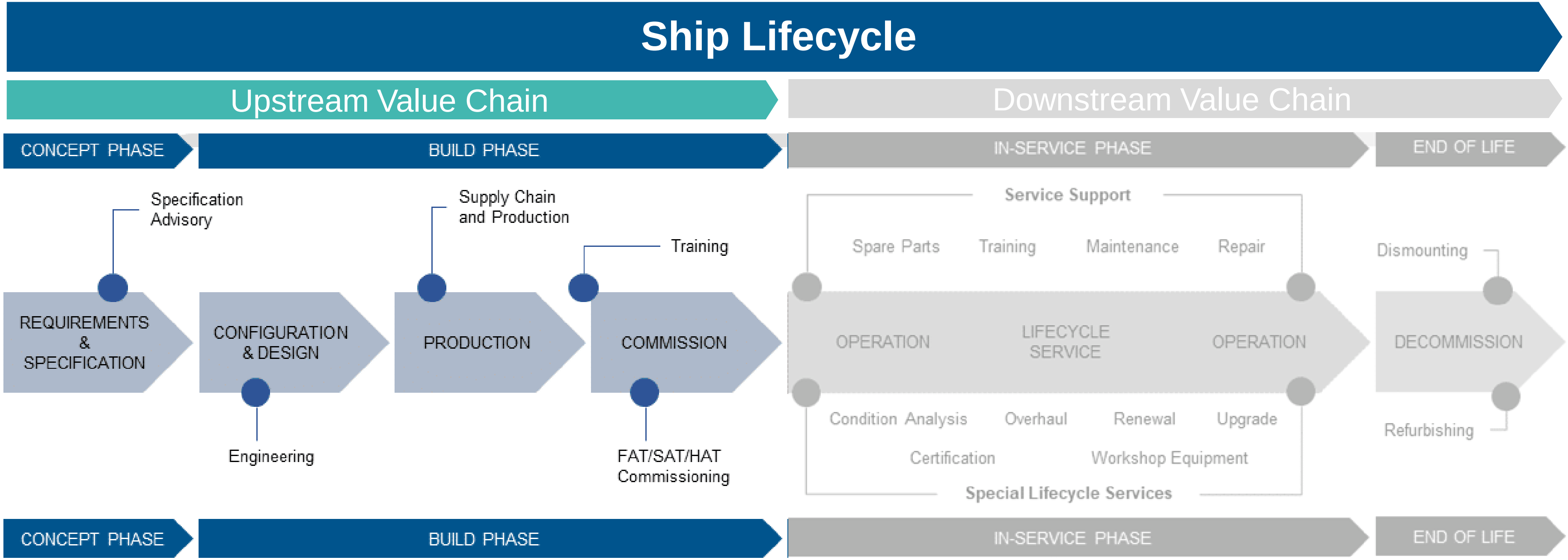
Opportunities in digitalization:

- 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**

Best Practices on Ship Design and Shipbuilding: Outline

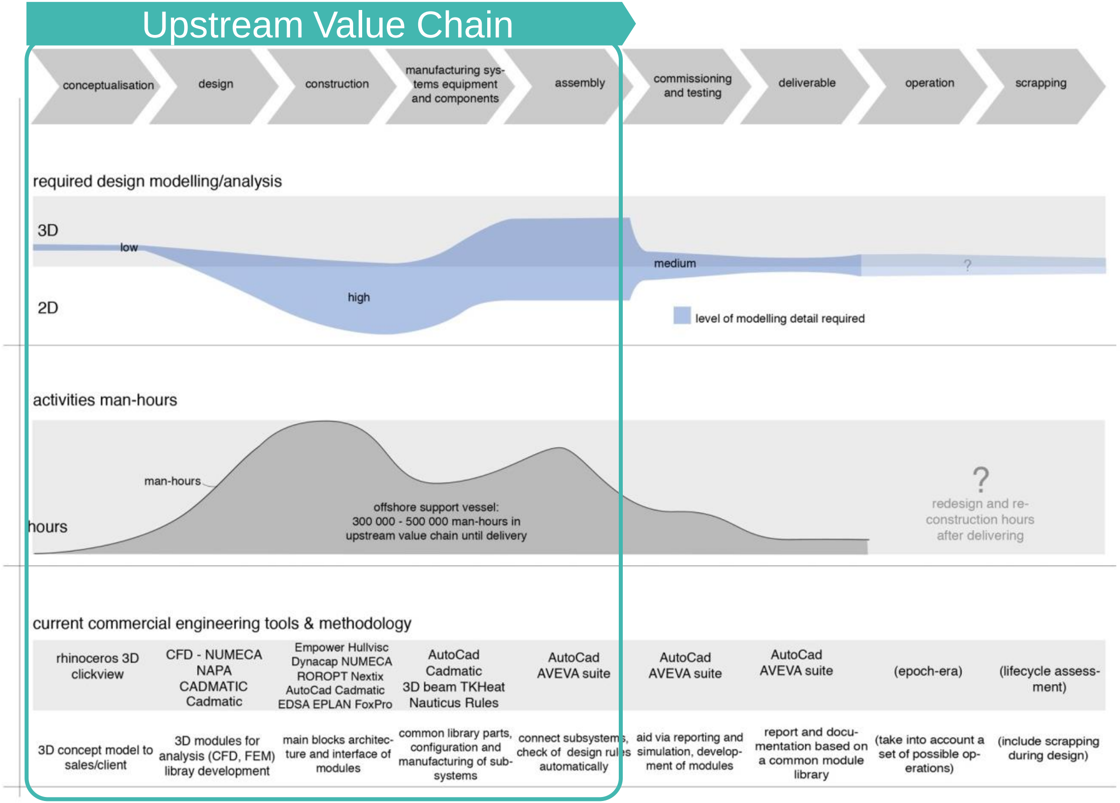
Recall: SD&SB Industry covers a wide range of services and activities throughout a vessel's lifecycle.

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/

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

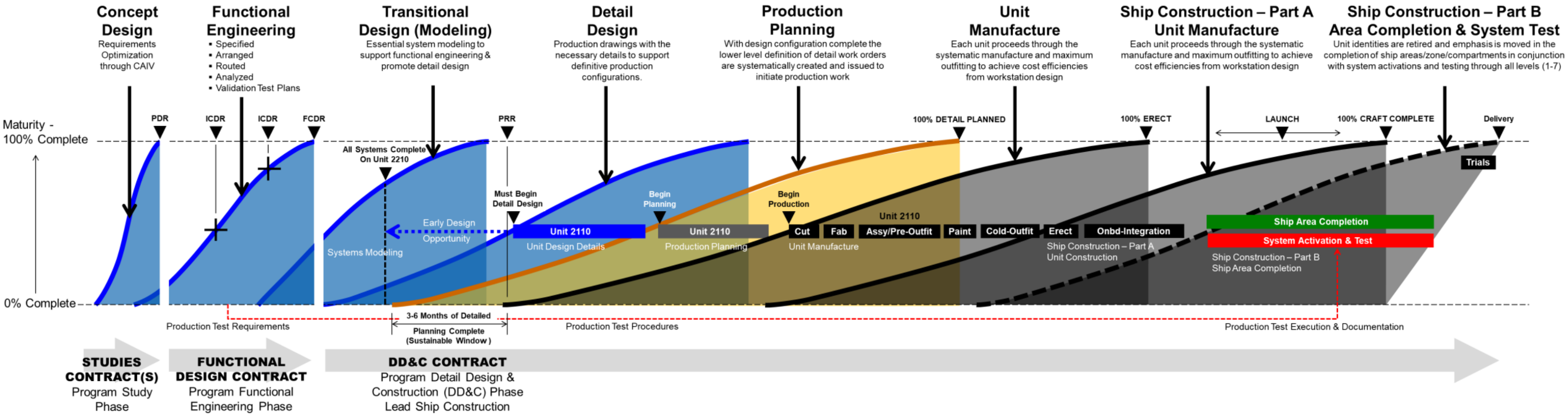


(Ulstein, 2015)

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

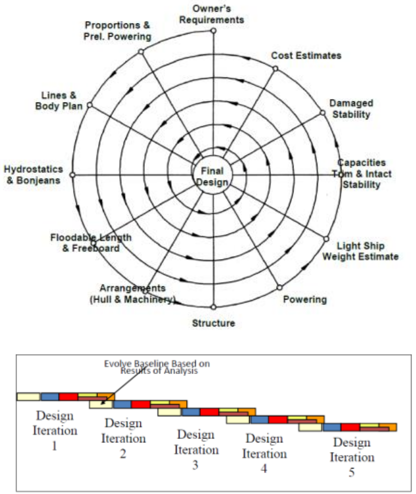
Upstream Value Chain



(Hitchcock, 2023)

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.

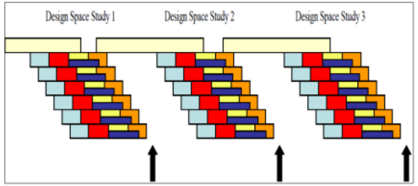
There are several approaches to ship design, from the traditional Design Spiral to more modern approaches such as model-based and set-based design.



Classic Design Spiral (Andrews 1981)

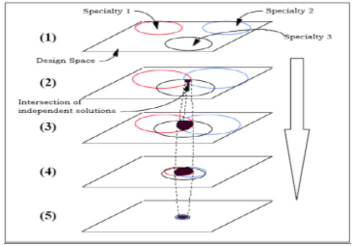
(Development and refinement of a single design, ~up to 8-12 weeks per design iteration)

(NAVSEA, 2012)



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 safety and meeting international regulations?)

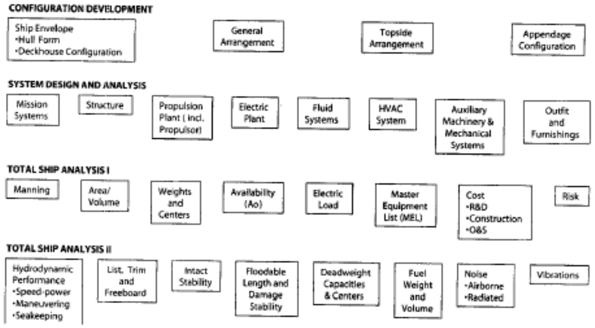
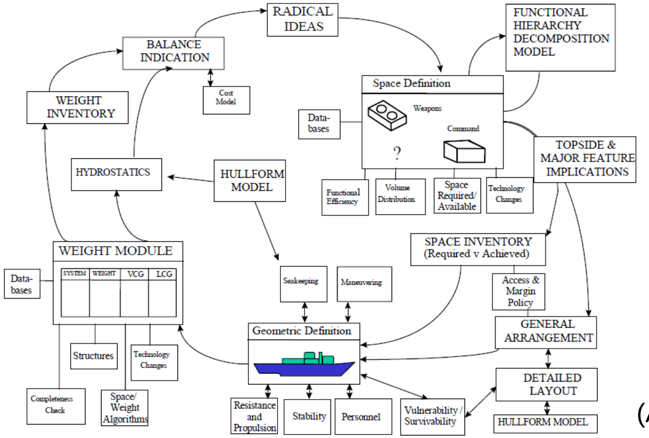


Figure 5.8 Concept Design Task Categories



(Andrews, et al., 2006)

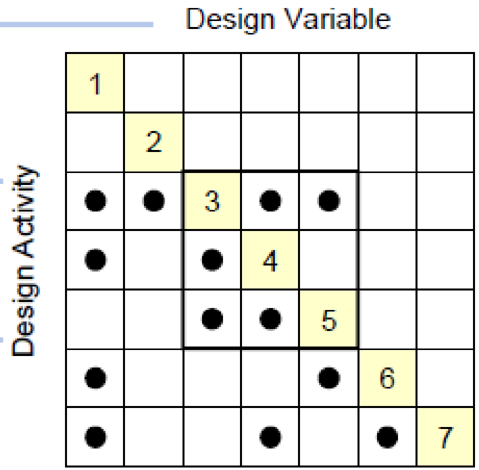
In the early stages of design, automated methods with low-fidelity data can be used for the systematic exploration of the design space. However, decision-making itself at this stage can't be automated due to close client collaboration and the lack of design information. Flexibility and collaboration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



Design Structure Matrix

(Doerry, 2009)

Design trade-offs:

Lower Costs vs Improved Vessel Performance & Mission Capabilities

Simplified Hull form vs Increased Ship Stability

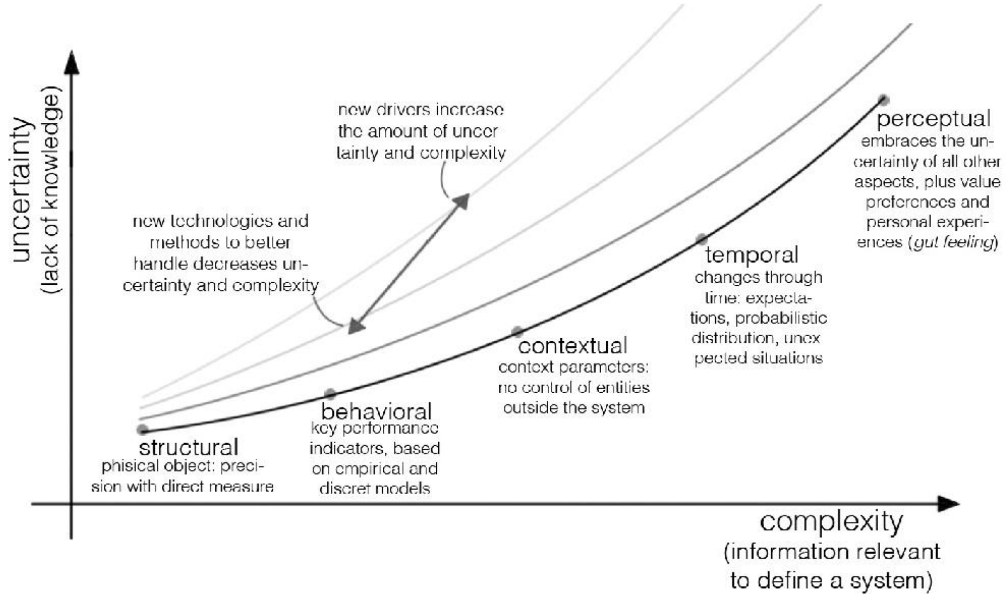
Simplified Structure vs Increased General Arrangement (GA) flexibility

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)

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)?

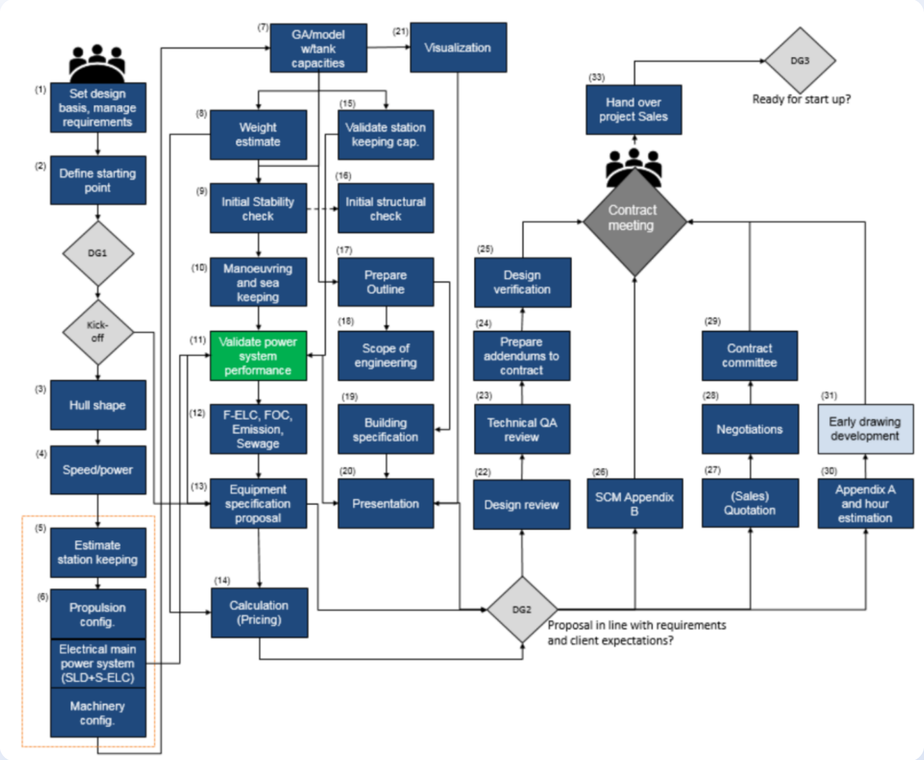
- **Analogous Estimate**: Historical data on one analogous system or subsystem (with adjustment factors)
- **Parametric Estimate**: Statistical analysis of historical projects (with weight ratios or derived equations)
- **Engineering Estimate**: Bottom-up detailed estimate (Too time-consuming)
- **Actual 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)

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:

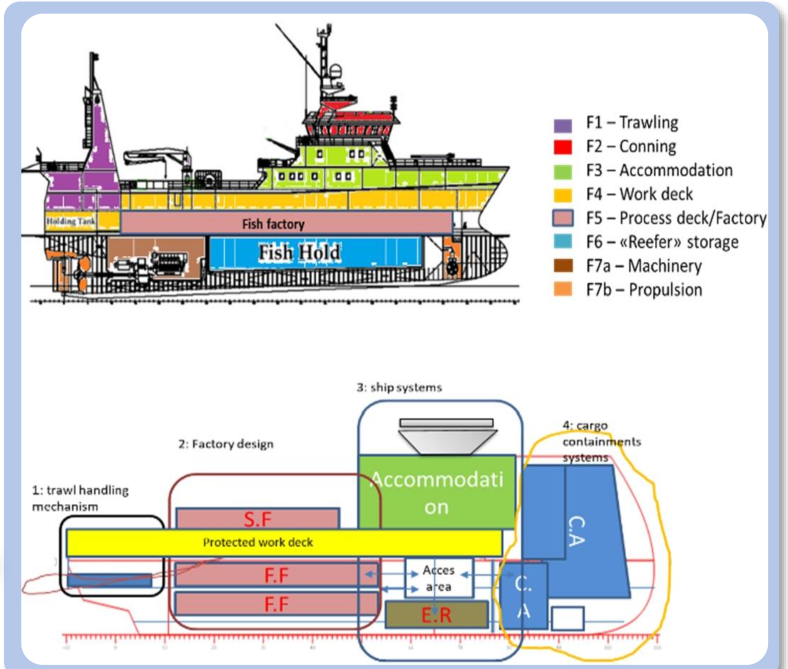
- Data is critical but low-fidelity information is typically available
- Lots of uncertainty from missing data, from client, from interdisciplinary team members
- Heavy reliance on contextual knowledge

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, 2004).	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.

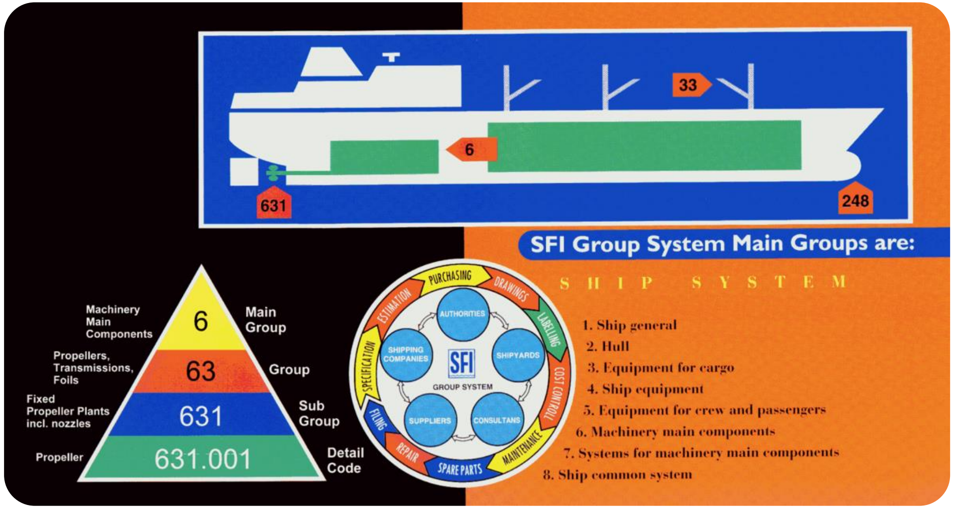
(Pettersen, 2018), Adopted from (Hubka & Eder (1998))



(Ebrahimi, et al., 2020)

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.)

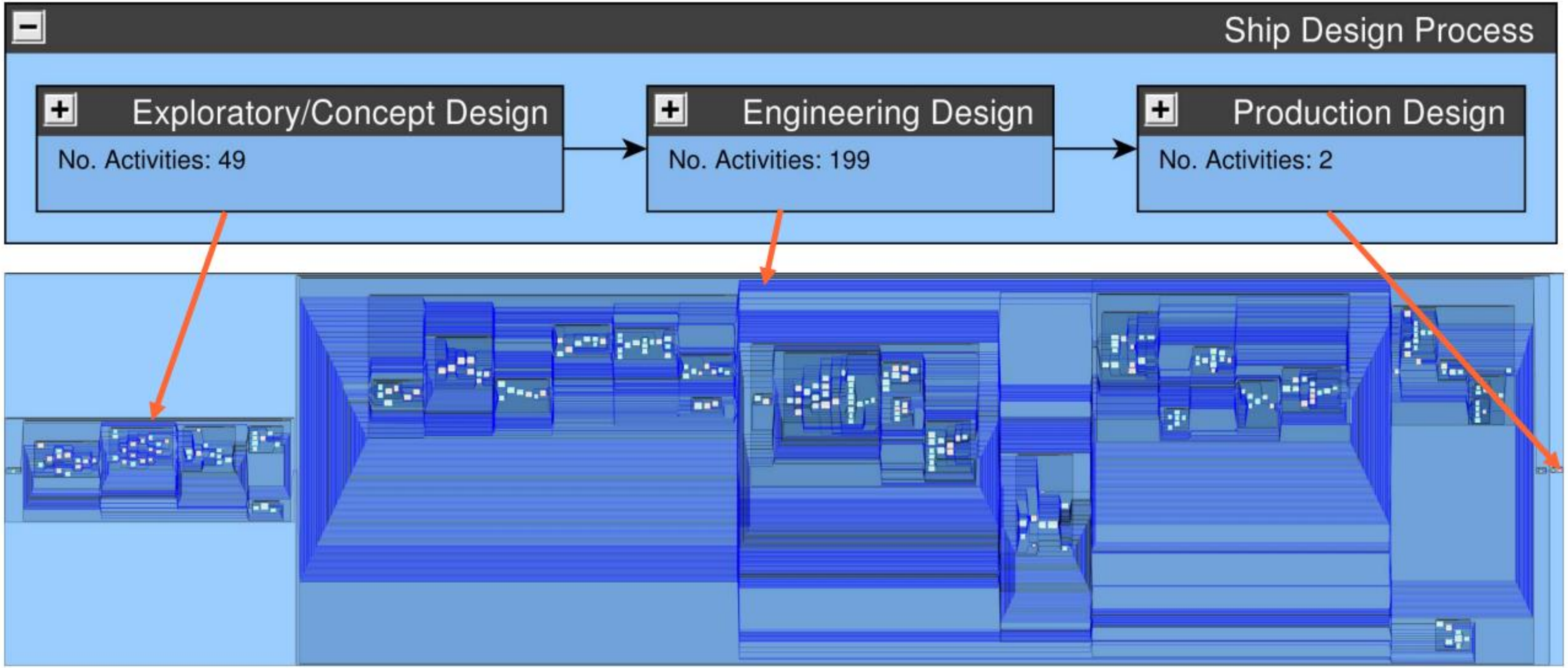
SWBS Breakdown

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

SFI Breakdown

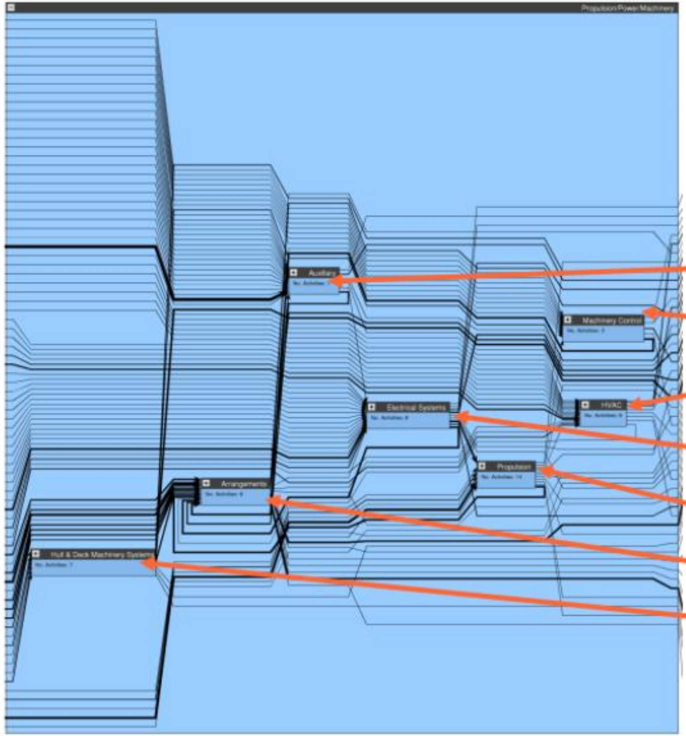
Developed in the 1970s to be a common code for maritime and offshore rigs
Up to ~700 components can be defined

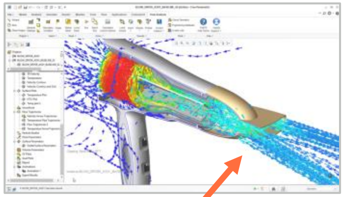
At Detailed Engineering stage, various design analyses and evaluation are performed, often concurrently among different teams to manage all the required systems that need to be evaluated.

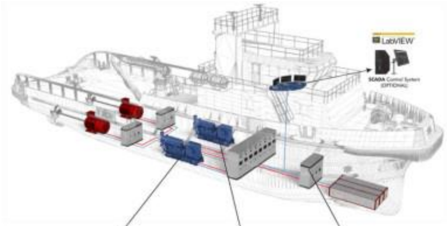


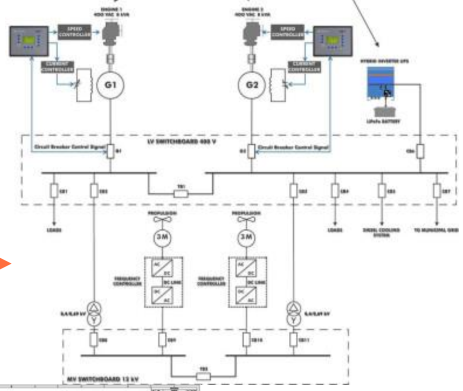
(NAVSEA, 2012)

Example concurrent workflow for SWBS 299, 300,500:

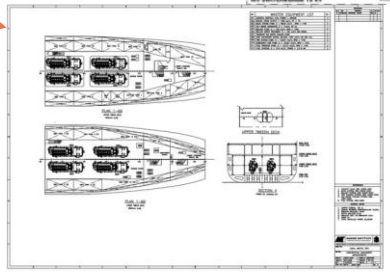








1. Auxiliary Systems
2. Machinery Control
3. HVAC (Heating, Ventilation, Air Conditioning)
4. Electrical Systems
5. Propulsion
6. Machinery Arrangements
7. Hull & Deck Machinery Systems



(NAVSEA, 2012)

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

(Gale, 2003)

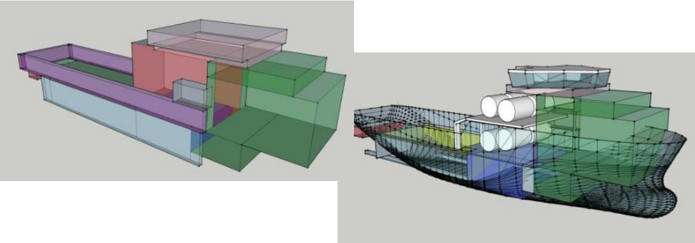
Technical deliverables increase dramatically during this stage.

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

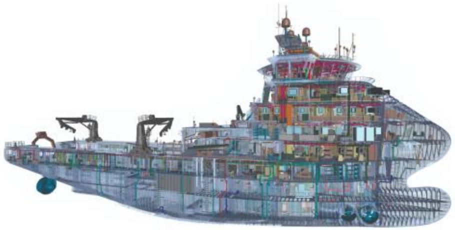
Common outputs from Detailed (Contract) Design

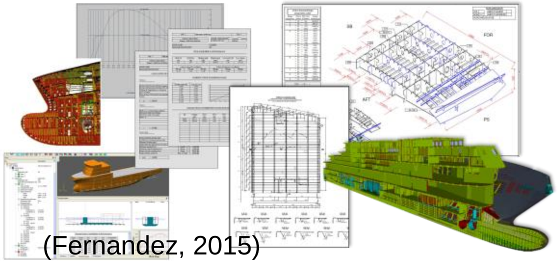
- Ship specification
- Lines drawing
- Appendage drawing
- General arrangements (outboard profile, inboard profile, all decks and holds)
- Topside arrangement
- Capacity plan
- Weight report (3-digit level, KG and LCG, 20-station weight distribution, gyradii)
- Structural design criteria manual
- Midship Section
- Steel scantling drawings (decks, bulkheads, shell expansion, typical sections, deckhouse)
- Machinery control system diagrams
- Propulsion and auxiliary machinery arrangement drawings (plan views, elevations, and sections)
- Propulsion shafting arrangement
- Propeller design
- Electric load analysis
- Electric power and lighting systems - One line diagrams
- Fault current analysis
- Navigation system diagram
- HVAC load analysis and design criteria
- Ventilation and air conditioning systems diagrams
- Piping systems analysis
- Diagrammatic arrangements of all piping systems
- Fire control diagram by decks and profile
- Mechanical systems arrangements, for example, deck, hull and ship control systems
- Living space arrangements (berthing, messing, sanitary, recreation, etc.)
- Commissary space arrangements
- Pilot House, Chart Room, and other working space arrangements
- Interior communications system diagram
- Master Equipment List (MEL)
- Preliminary ship manning document
- Pollution control systems report
- Loading conditions
- Floodable length curves
- Trim and stability booklet
- Damage stability analysis
- Endurance fuel analysis
- Hydrodynamic model test results, for example, resistance, propeller open water, self-propulsion, maneuvering, seakeeping, etc. and performance assessment reports
- Stack gas flow analysis
- Evaluations of other aspects of required performance
- Availability analysis (Ao)
- Maintenance Plan
- Supportability Plan
- Crew Training Plan
- T&E Plan
- Safety analysis
- Procurement specifications for long-lead-time and other important outfit components, for example, main propulsion engines, diesel generators, reduction gears, anchor windlass
- Models and Mockups
- Cost estimate
- Technical risk assessment and risk management plan
- Initial regulatory body review
- Building plan
- Budget control list (estimated weight of all required material by material family or cost code)
- Production plan

(Gale, 2003)



(Vestbøstad, 2011)





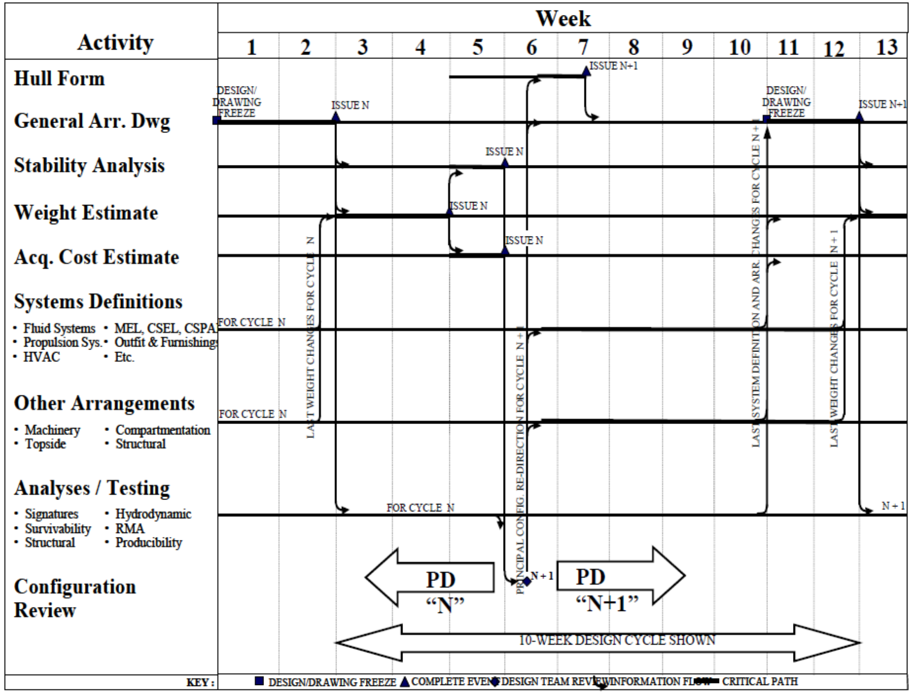
(Fernandez, 2015)

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)

Design Definition Tasks

Design Evaluation Tasks

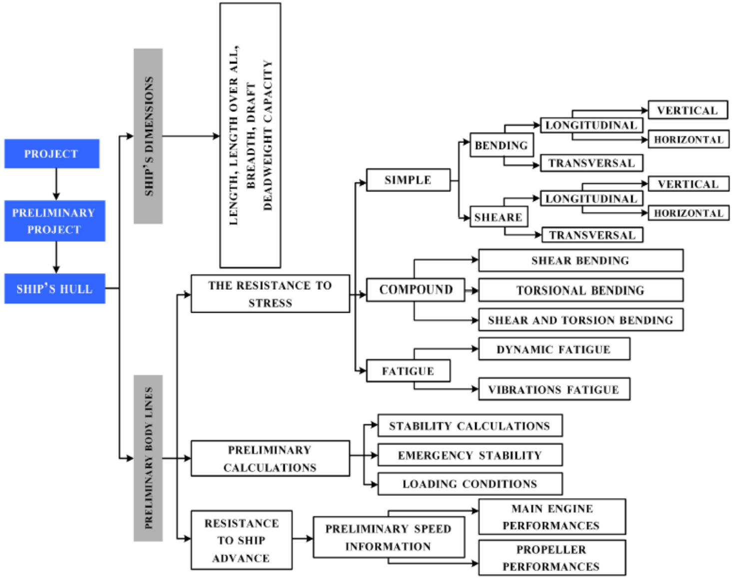
Design Compliance and Review Tasks



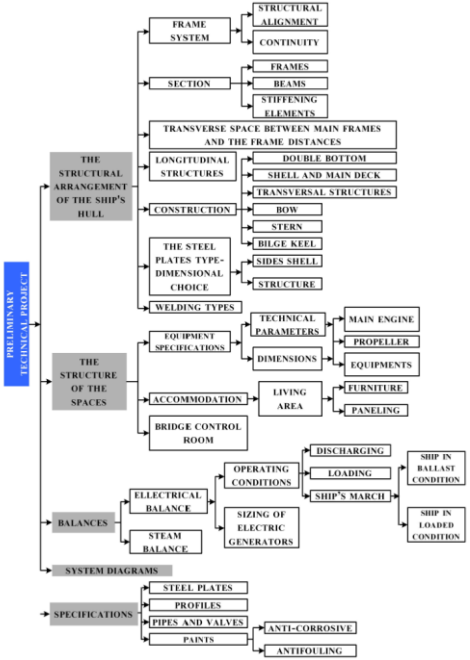
(NAVSEA, 2012)

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

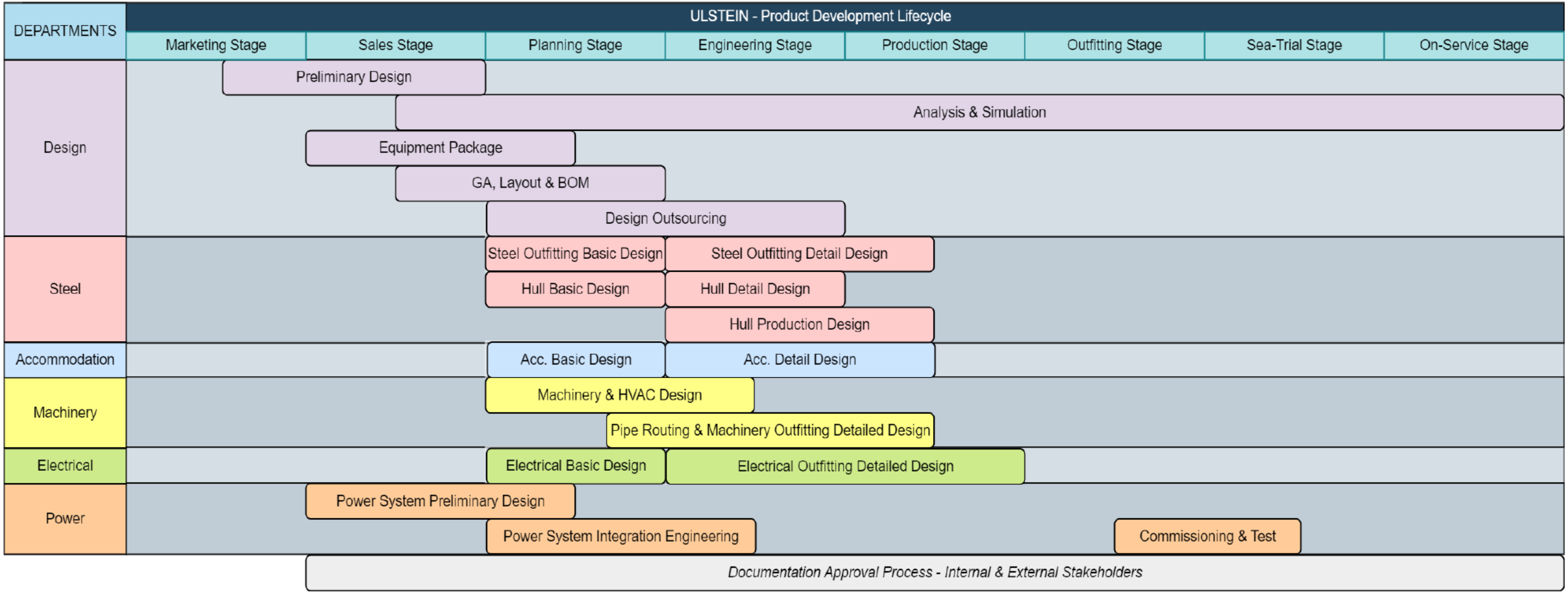


Detailed Project Design

(Manea & Manea, 2023)

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

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



(Thamby, 2023)

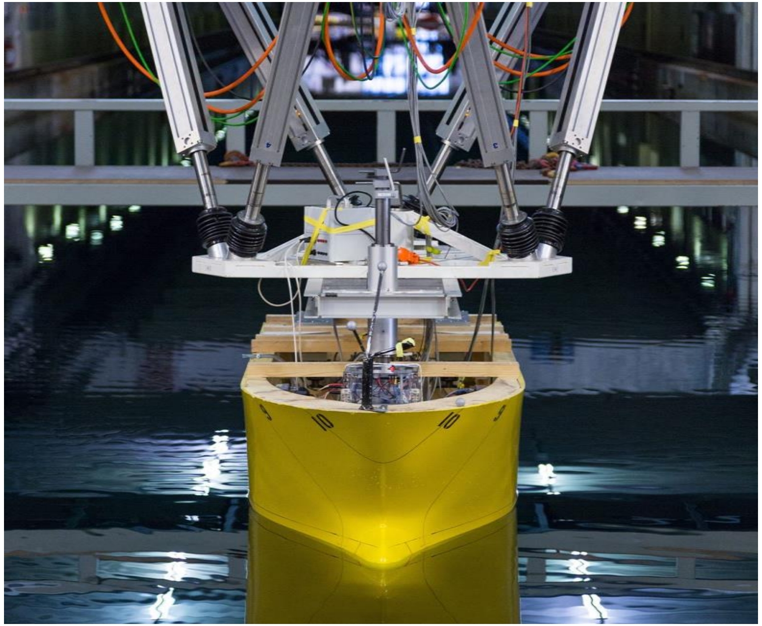
NOTE: These task decompositions are interpretations of what is needed at the detailed design and may vary from company to company.

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

Examples for Hydrodynamics Tests:

Resistance and Propulsion Tests	• 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. • 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. • 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.
Propulsor Tests	• Evaluating wake characteristics of the hull to assist in propeller design and optimization. • Evaluating alternative propulsors or improving the accuracy of propulsor efficiency predictions. • Determining propulsor cavitation or noise characteristics. For some ships where these characteristics are KPPs, such tests may be essential to confirming such performance.
Maneuvering Tests	• 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. • Evaluating alternative control surfaces relative to maneuvering requirements.
Ship Motions Tests	• 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. • Predicting slamming characteristics.
Special Hydrodynamic Tests	• Determining astern powering or stopping characteristics. • Flow visualization. This may be needed to align appendages, or for special mission ships, to assist in minimizing hydrodynamic noise. • Fin stabilizer alignment. • Determination of propeller-induced vibratory forces. • Shaft and strut alignment. • Topside airflow. • Dynamic Stability. The increasing interest in dynamic stability and unusual hull forms may require tests to assess stability characteristics in special conditions. • Examining special hydrodynamic phenomena. An example of this might be the behavior of water within a well under specific conditions. • Determining structural loads. These may be required for structural design purposes or to investigate operating constraints.

(NAVSEA, 2012)



Towing Tank Tests
(sintef.no)

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:

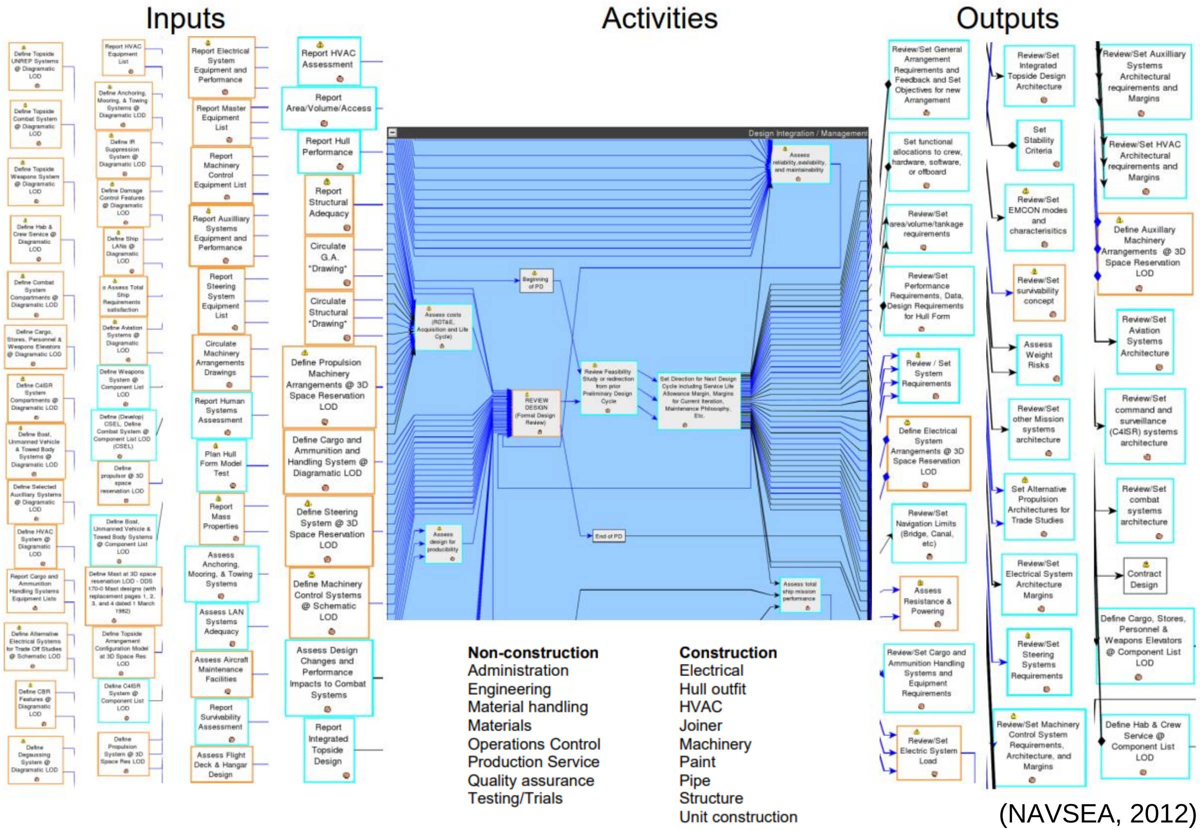
- Passenger Ship Safety Certificate
- International or Domestic Safety Management Certificate
- MCA approval for manning
- MCA approval for passenger counting and recording
- if over 24m but under 400GT a Declaration on Anti-Fouling Systems
- International Anti-Fouling Certificate (instead of a Declaration) 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)

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

Managerial Tasks

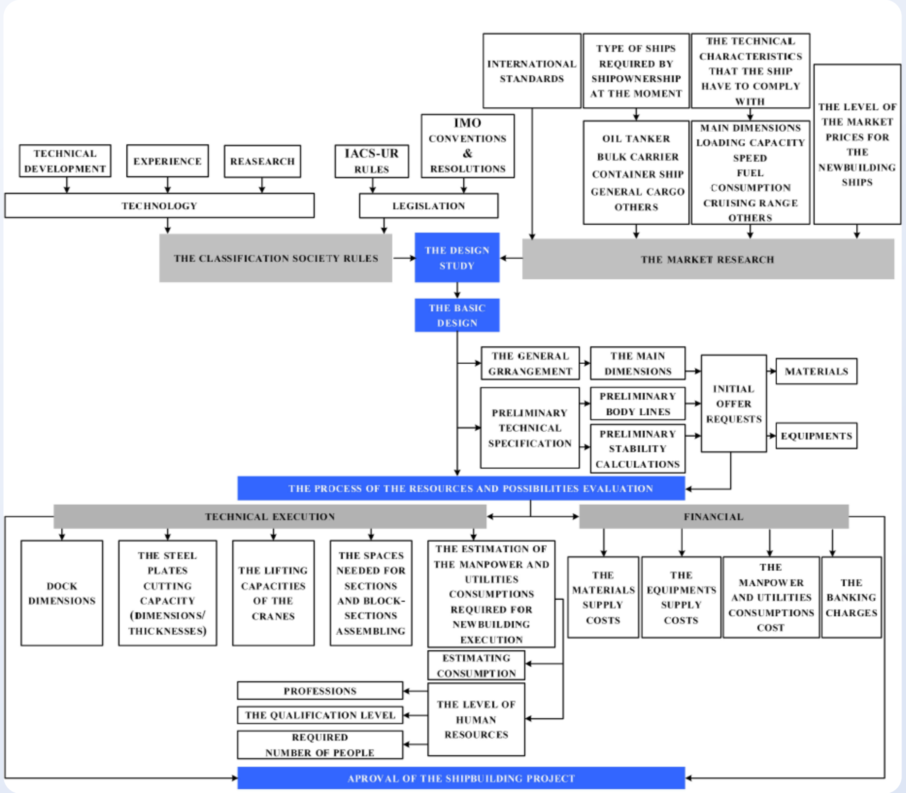
Engineering Tasks



(NAVSEA, 2012)

Detailed Design – Sample Process Execution

Design Stages at Constanta Shipyard



(Manea & Manea, 2023)

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

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.

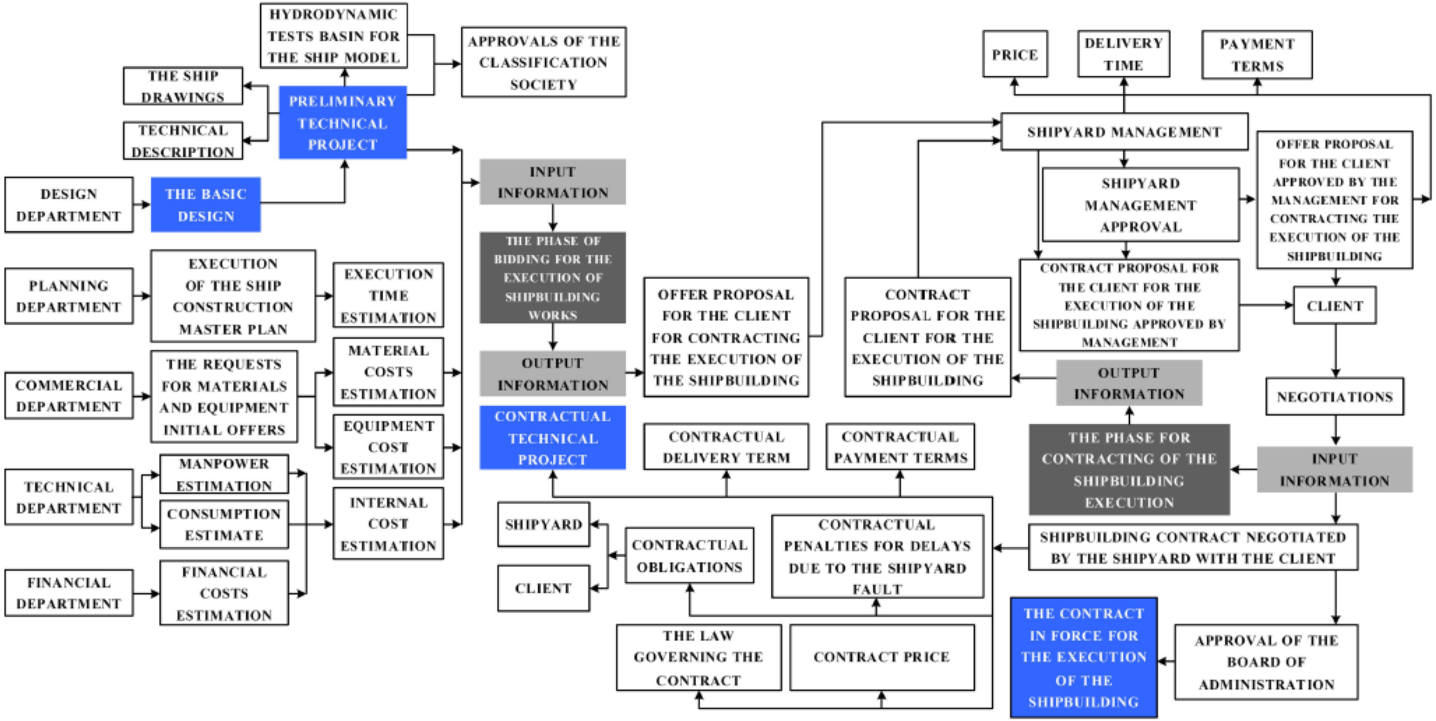
Main Goal of ship designers: Correctly define and evaluate functional parts or systems using existing tools (focus on individual specialized tasks)

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 in generated

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

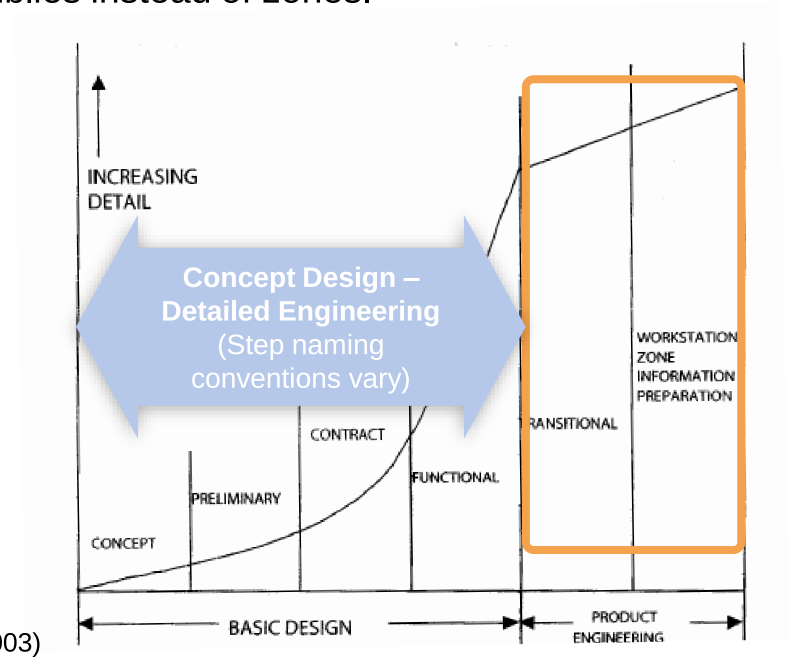


(Manea & Manea, 2023)

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

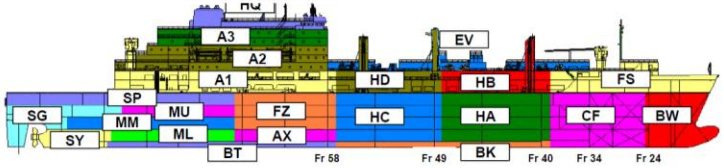
When a contract is won, the ship design and design outputs are converted so they are production-ready. This phase is often called ‘transitional design’ which involves the conversion of the functional ship outputs into Block and or Zone orientation based on the facilities available in the yard. The ship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

Zone Breakdown



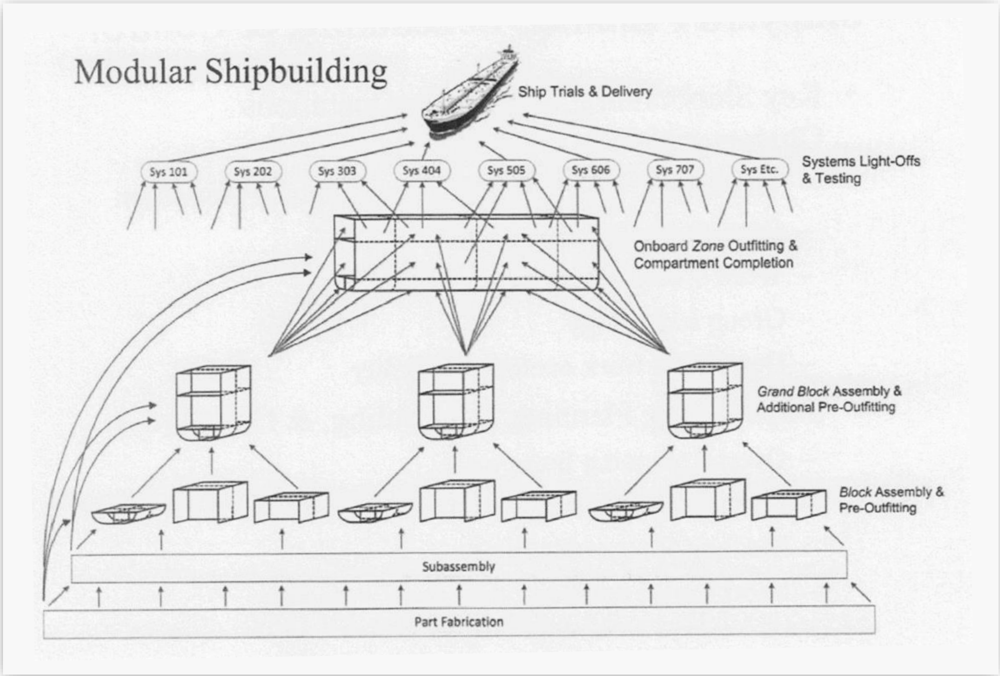
Type	Zone	Description	Type	Zone	Description
Cargo	BK	Bilge Keel & Double Bottom	Mach	SG	Steering Gear
Cargo	HA	Multipurpose Hold #1	Cargo	FZ	Freeze/Chill
Cargo	HC	Multipurpose Hold #2	Cargo	CF	Cargo Fuel Tanks
Mach	AX	Auxiliary Machinery Room	Accom	A3	Accommodations Upper
Accom	A1	Accommodations Lower	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

(Pal, 2015)

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).



(Koenig, 2019)

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

Steel Parts

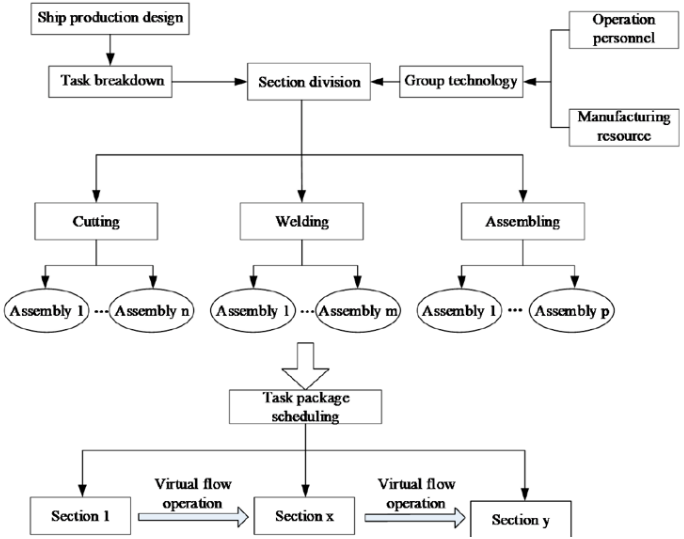
Steel Blocks

Steel Assemblies

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.

Shop floor planning



(Song & Zhou, 2021)

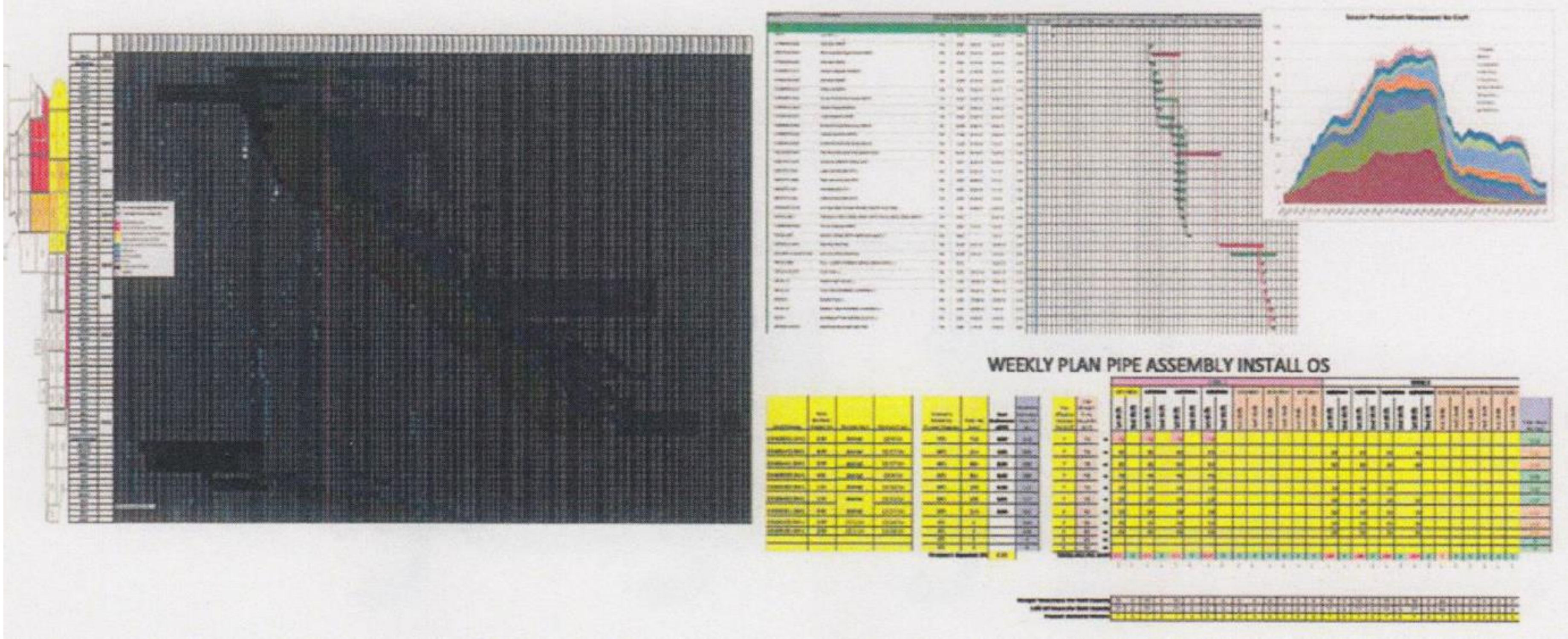
Cutting

Welding

Steel transport & assembly

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.



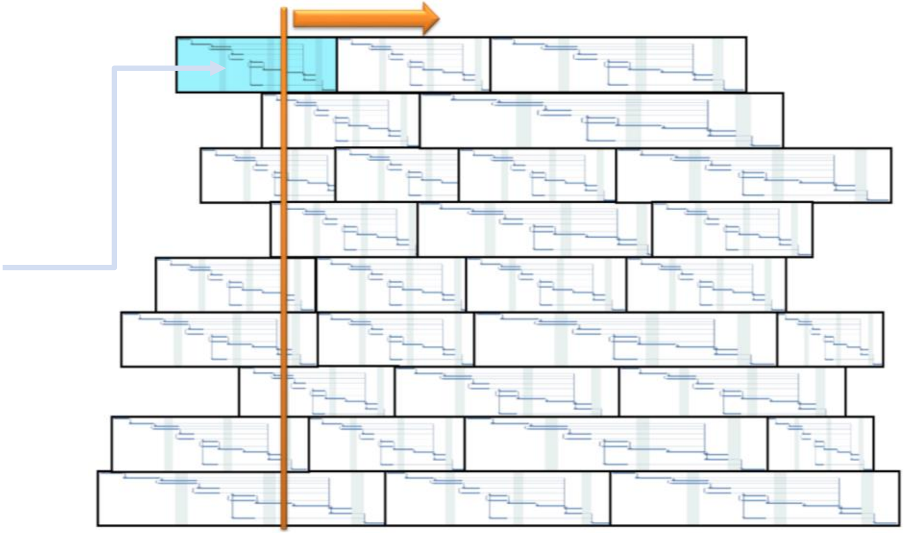
(Koenig, 2019)

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.

Stage function	design	planning	Production engineering	production	purchasing	commercial	quality	Human resources	output
strategy	Product development	Corporate Plans	Production Strategy	Facility plans	Supplier relations	Market Strategy	Quality Certificates	Workforce strategy	good enquiries
contract	Specification	Projexct strategy	Production strategy	Production strategy	Long lead items	Contract	Quality plan	Resource plan	contracts
design	Functional design	Tactical plan	Design for production	Work station	Purchase orders	Cost analysis	Design quality	Training needs	Design Approval
materials	Purchase Specification	Purchase plan	Value analysis	Stores control	Purchas orders	Material costs	Supplier ratings	Training needs	Available materials
Manufacture	Deail design	Detail schedules	Workstation analysis	Part manufacture	Materials supply	Cost monitoring	Quality control	Safety	Parts ready
assembly	Deail design	Progress monitor	Work study	Unit assembly	Equipment supply	Cost Monitoring	Quality control	Safety	Units ready
construction	detail design	Progress monitor	Work study	Ship construction	Sub-contracts	Cost monitoring	Quality control	Safety	Ship complete
testing	Test Specification	Test Schedules	Production review	Tests trials	Supplier performance	Test results	Test procedures	Staff	Ship acceptance
delivery	Design review	Contract review	Methods review	Review	Purchase review	Contract review	Guarantee	Personnel audit	Repeat business

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

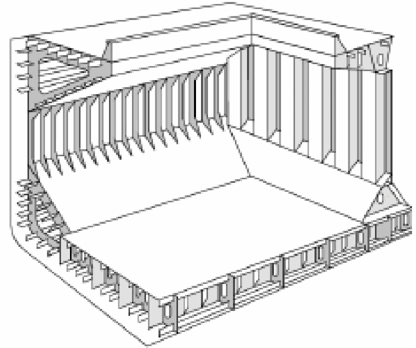
(Bruce, G., 2021)



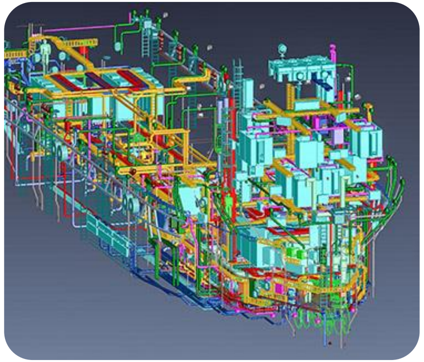
Simultaneous Scheduling

(Sollid, F. 2016)

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



(Bonnin-Pascual, et al., 2012)



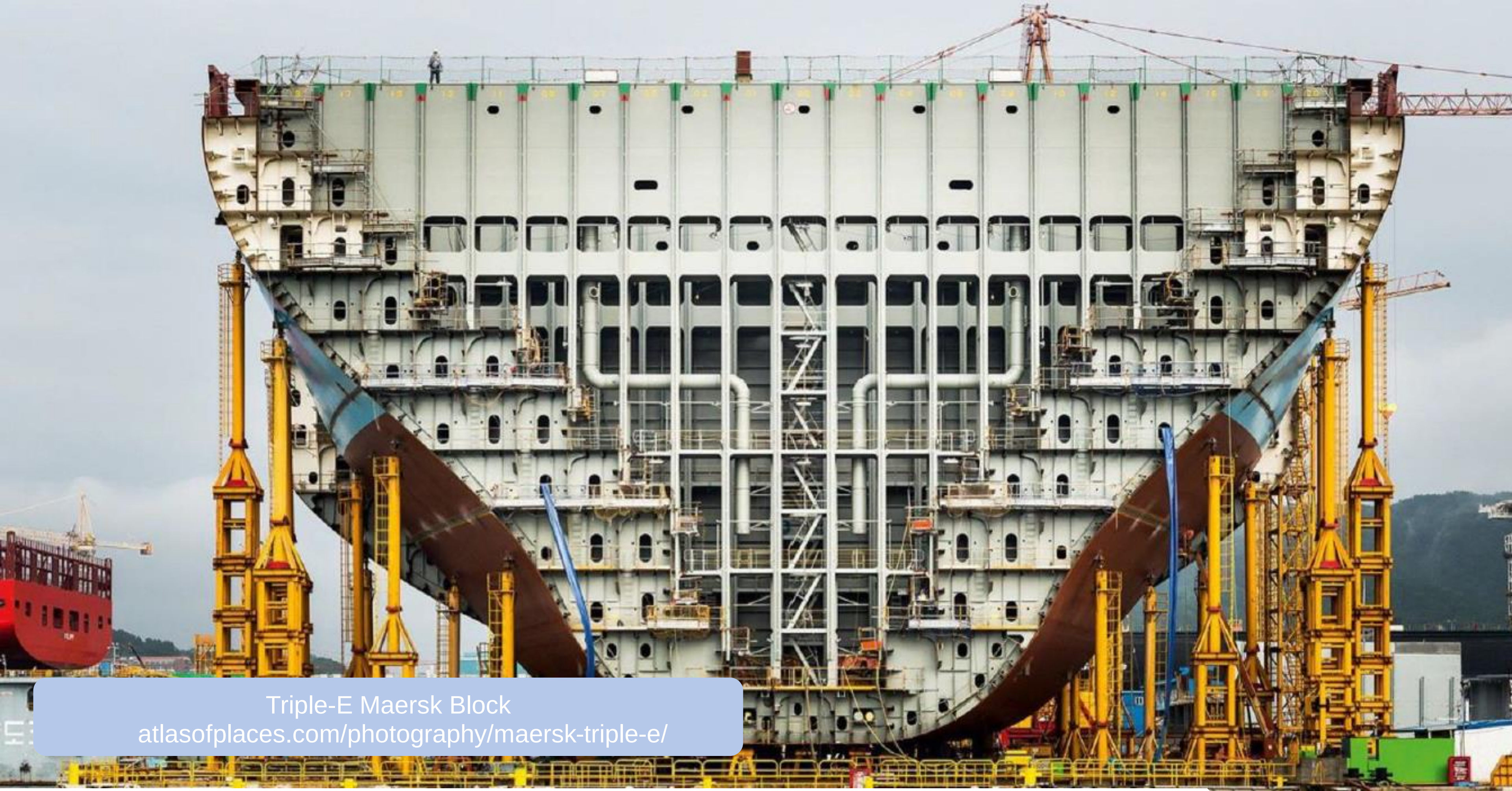
Structure (Hullform + Superstructure)
Hull Shell Plating, Decks, Stiffeners, Rudders, Castings, etc.

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/

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 outfitted 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.

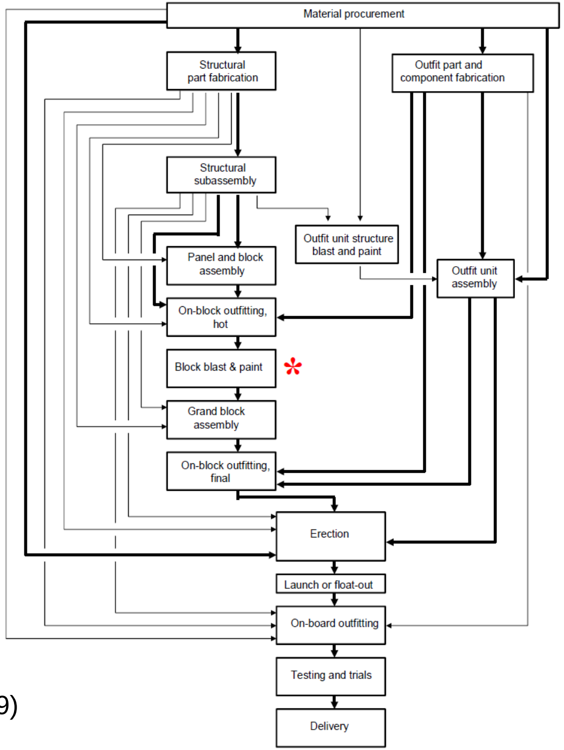
Delay in installation allows for concurrent design and production, but much more costly to install

Figures from (Sanchez, 2018)

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)

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

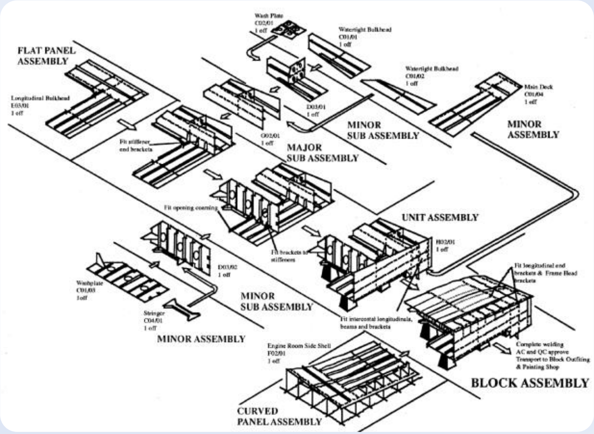
Shipyards need to understand how EoS affects their business and how they can strategically keep costs low by increasing volume or scale.

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.

Hyundai's Mipo shipyard in Ulsan, South Korea (Fritzell, 2022)

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.



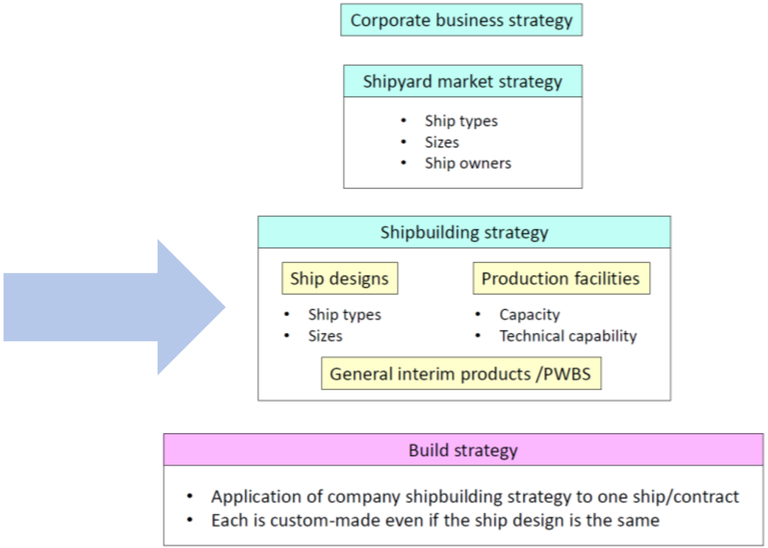
As of late it is much more expensive to build the hull in Europe due to high labor costs and throughput costs. For example, in 2013, European yards had a lower productivity average compared to shipyards in Japan and Korean.

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

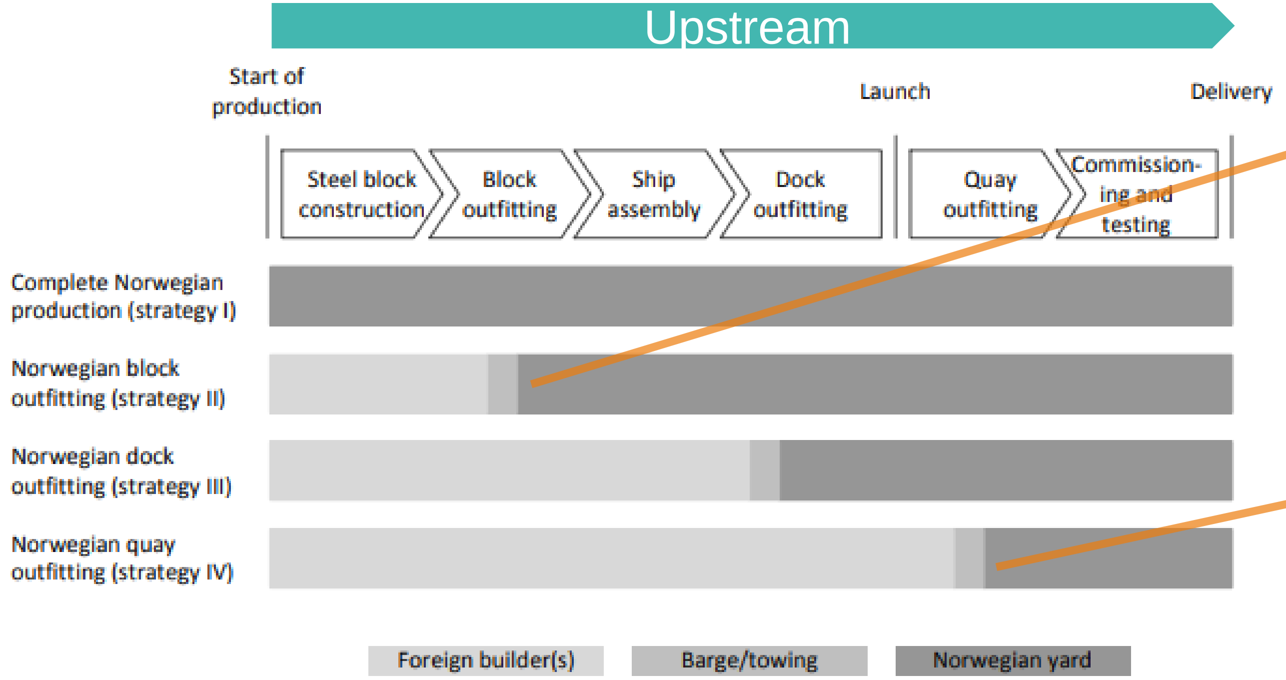
METRIC		JAPAN			KOREA			CHINA			EUROPE		OVERALL AVERAGE
	LOW	AVERAGE	HIGH	LOW	AVERAGE	HIGH	LOW	AVERAGE	HIGH	LOW	AVERAGE	HIGH	
Technology Level (Best Practice Level)	4.1	4.45	4.7	4.2	4.5	4.7	3.6	3.8	4	4.3	4.6	4.8	4.34
Productivity - CGT/Employee Year Incl. SC	173	201	211	57	82	89	13	22	29	31	43	140	82
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 t/m^2	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 Shipyard Area	0.095	0.104	0.199	0.067	0.137	0.199			0.252	0.192	0.266	0.384	0.152
CGT/Shipyard Total Area CGT/m^2	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 TE/m^2	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 CGT/m^2	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 CGT/m^2	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

Prof. T. Lamb, 2013, Class 10, p. 24



(Koenig, 2019)

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.

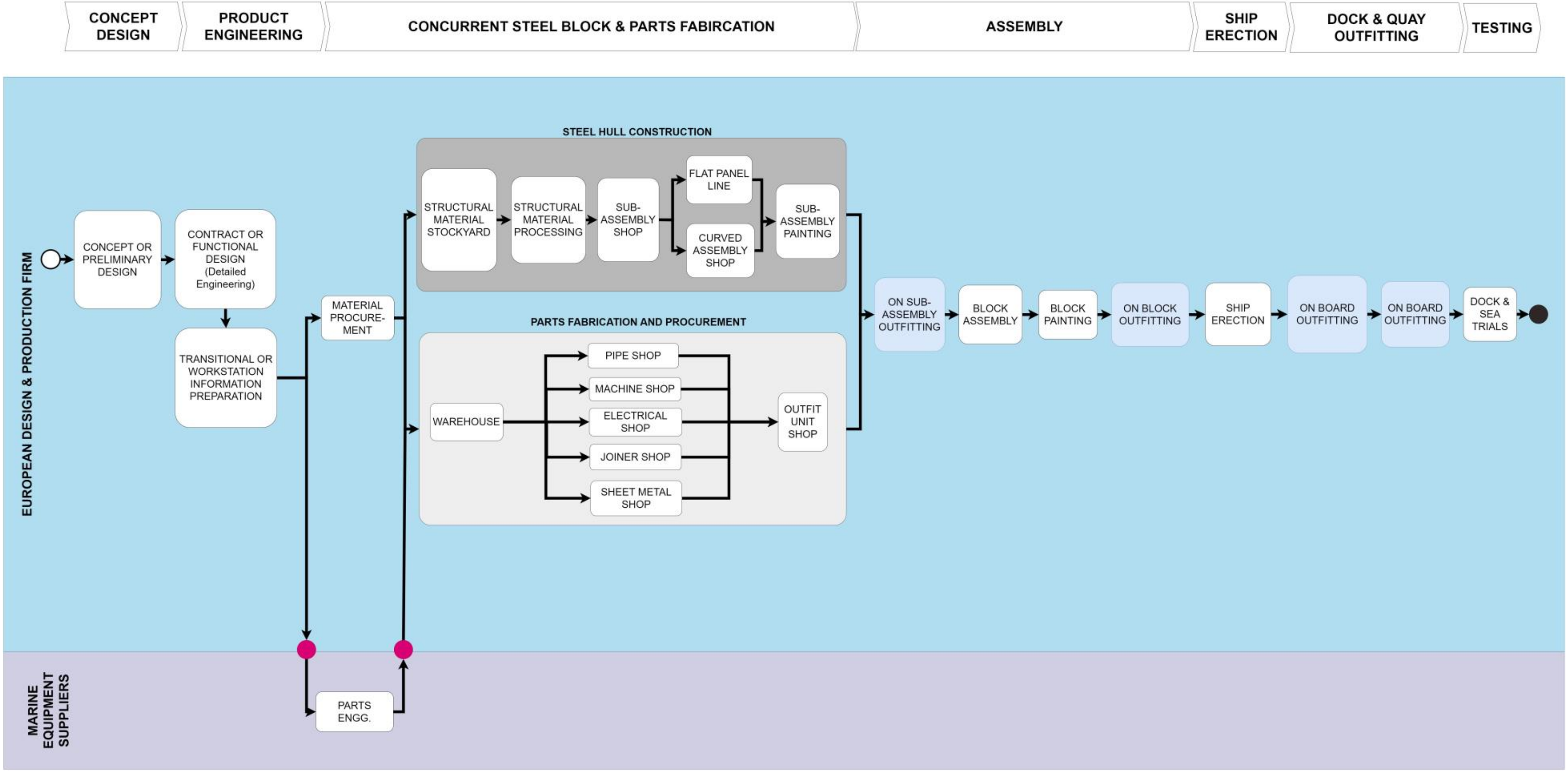


(Semini, et al., 2018)

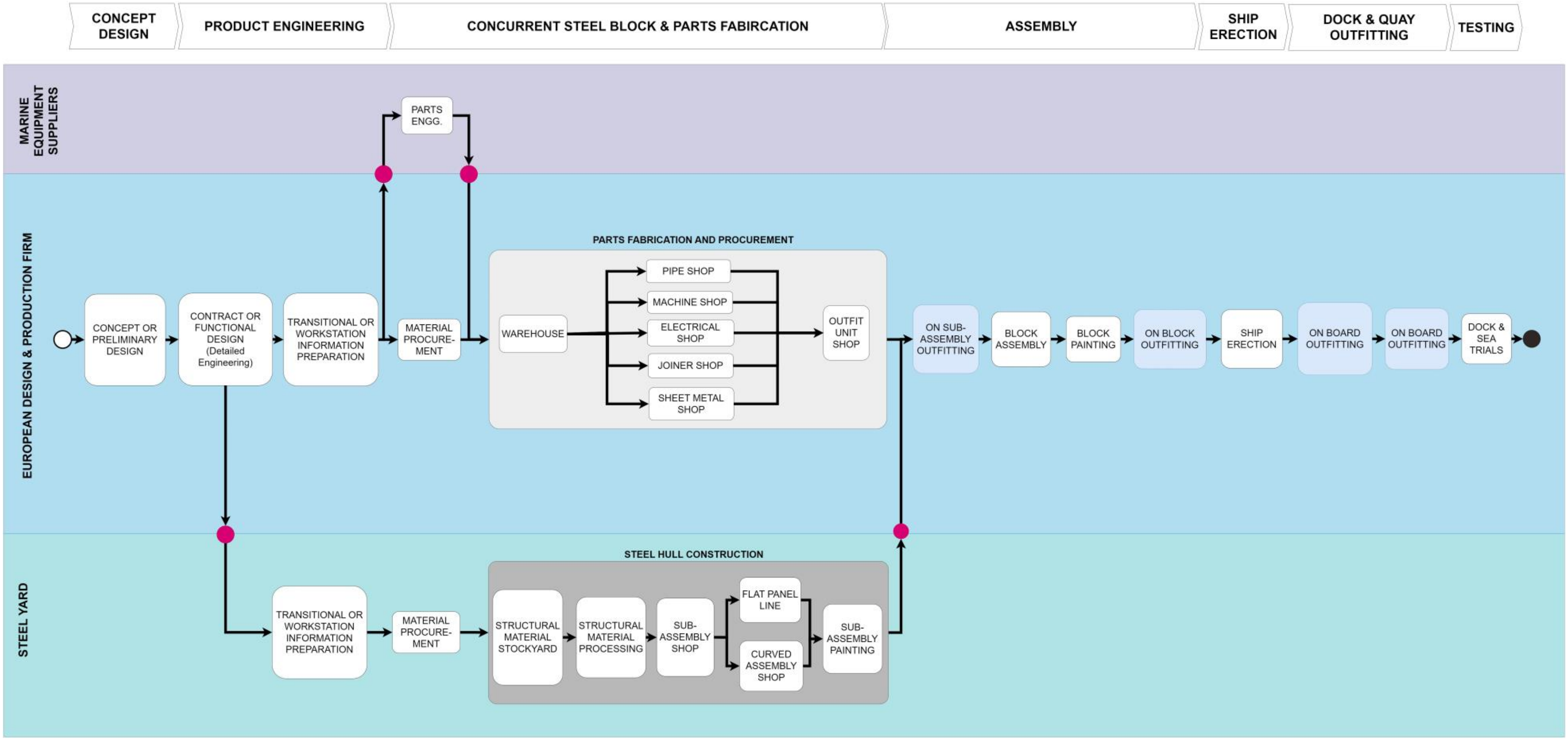
Pre-outfitted blocks shipped for assembly

Ship already launched, towed for outfitting and painting

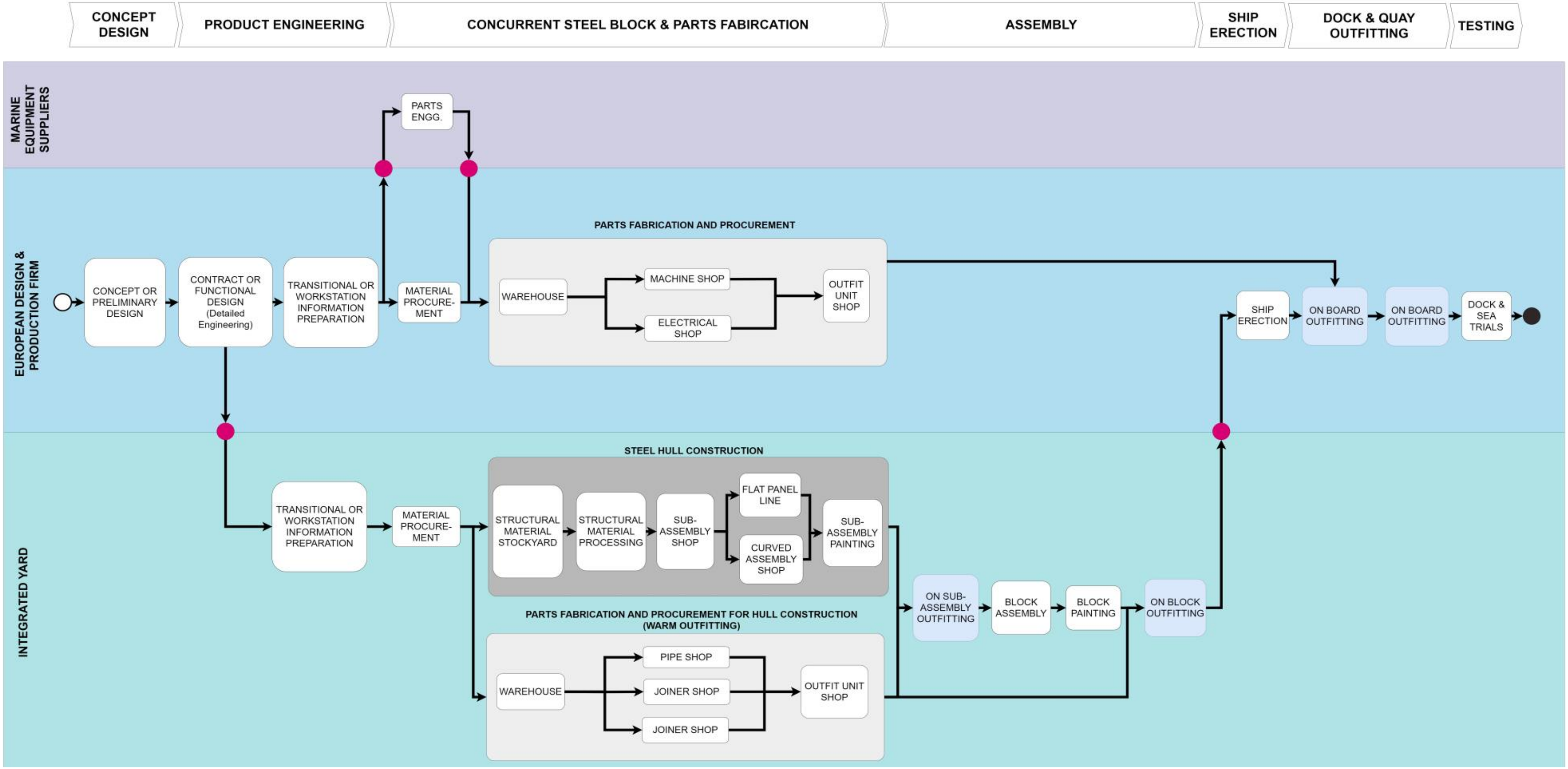
STRATEGY I - Complete Norwegian Production



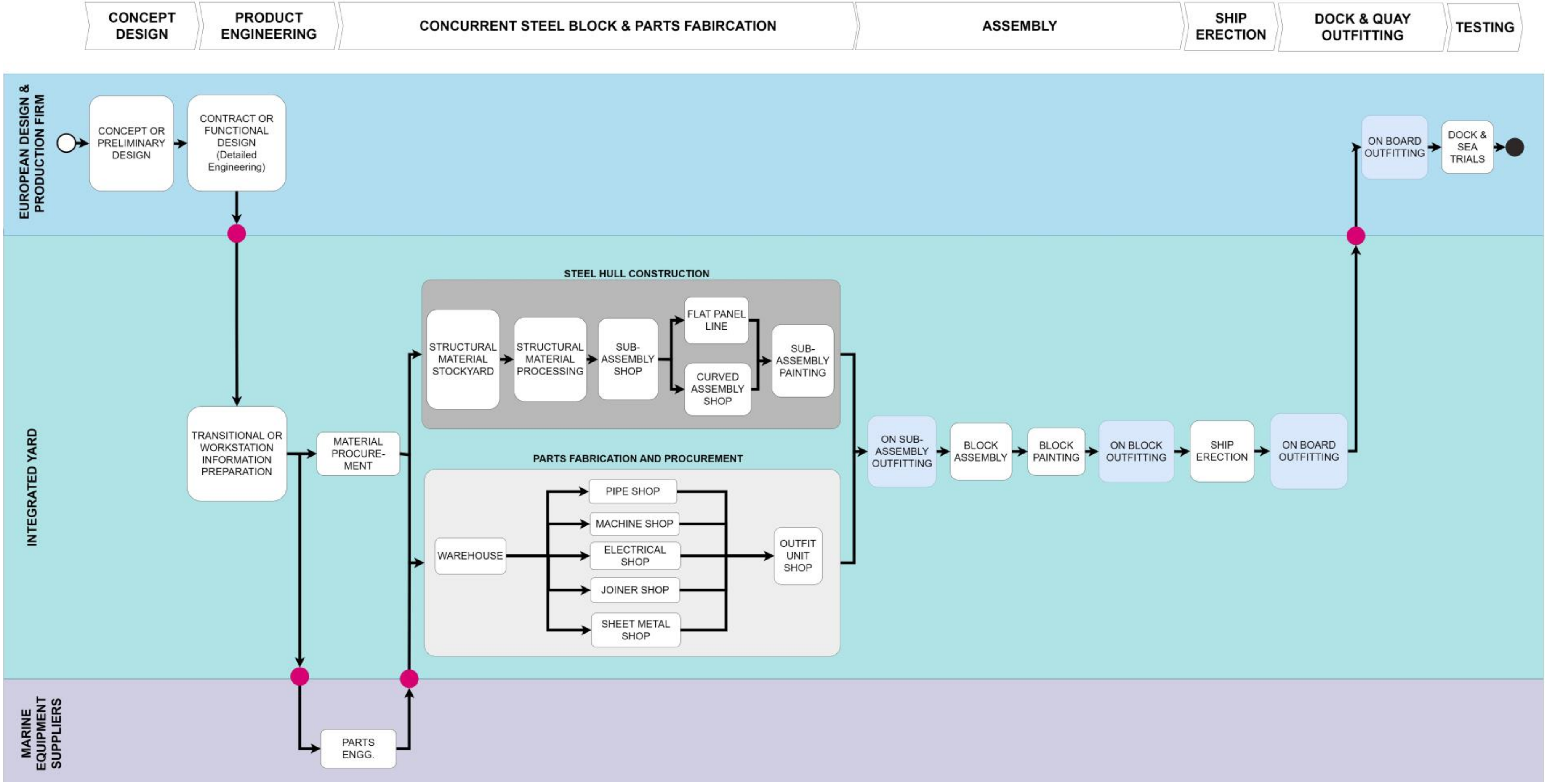
STRATEGY II - Block Outfitting and Assembly in a Norweigan Yard (Hull Construction Abroad)



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

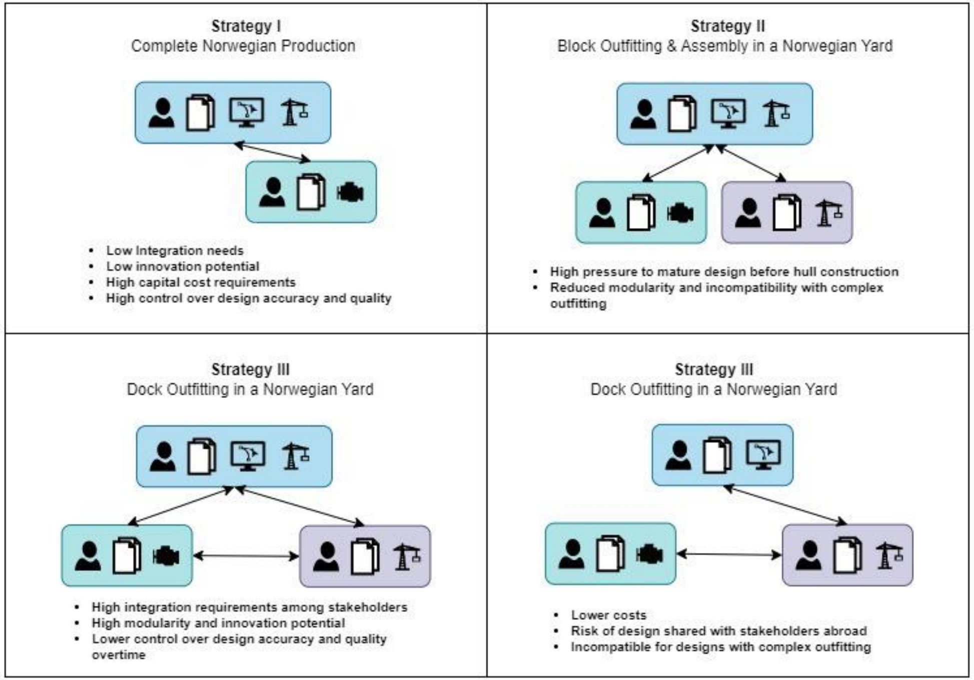


STRATEGY IV - Quay Outfitting



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.

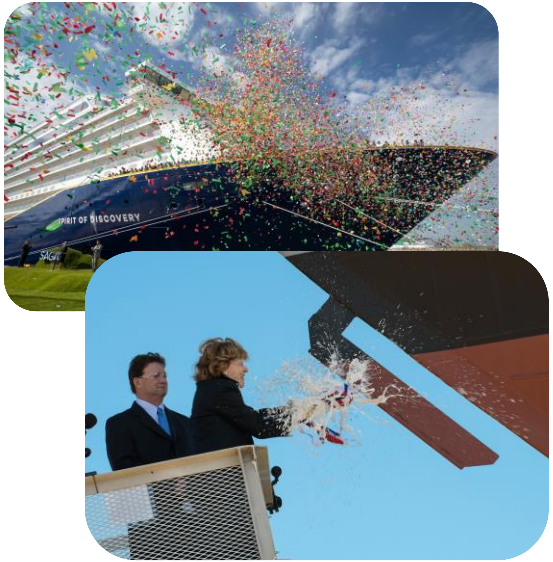


Integration Risks for Different Strategies

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	Commissioning	Testing and Delivery

Side and Slipway Launching



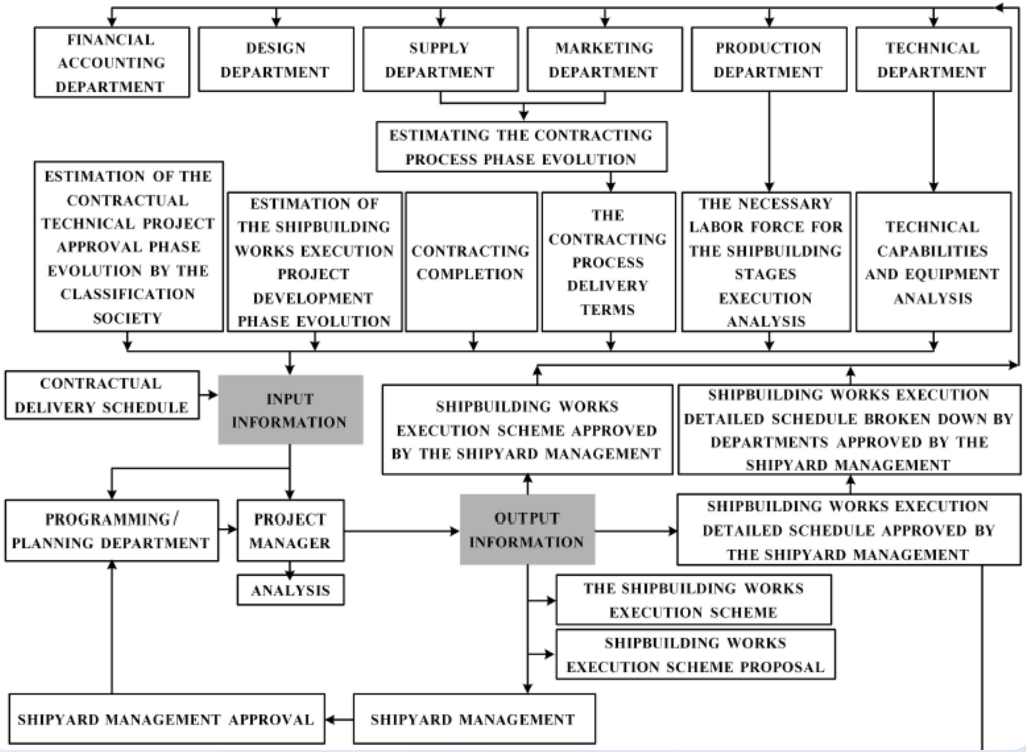
Ship Ceremonial Christening and Commissioning

Turning Tests and Bollard Pull Testing

Construction – Sample Process Execution

Shipbuilding Stages at Constanta Shipyard

Pre-acceptance of the Construction Plan



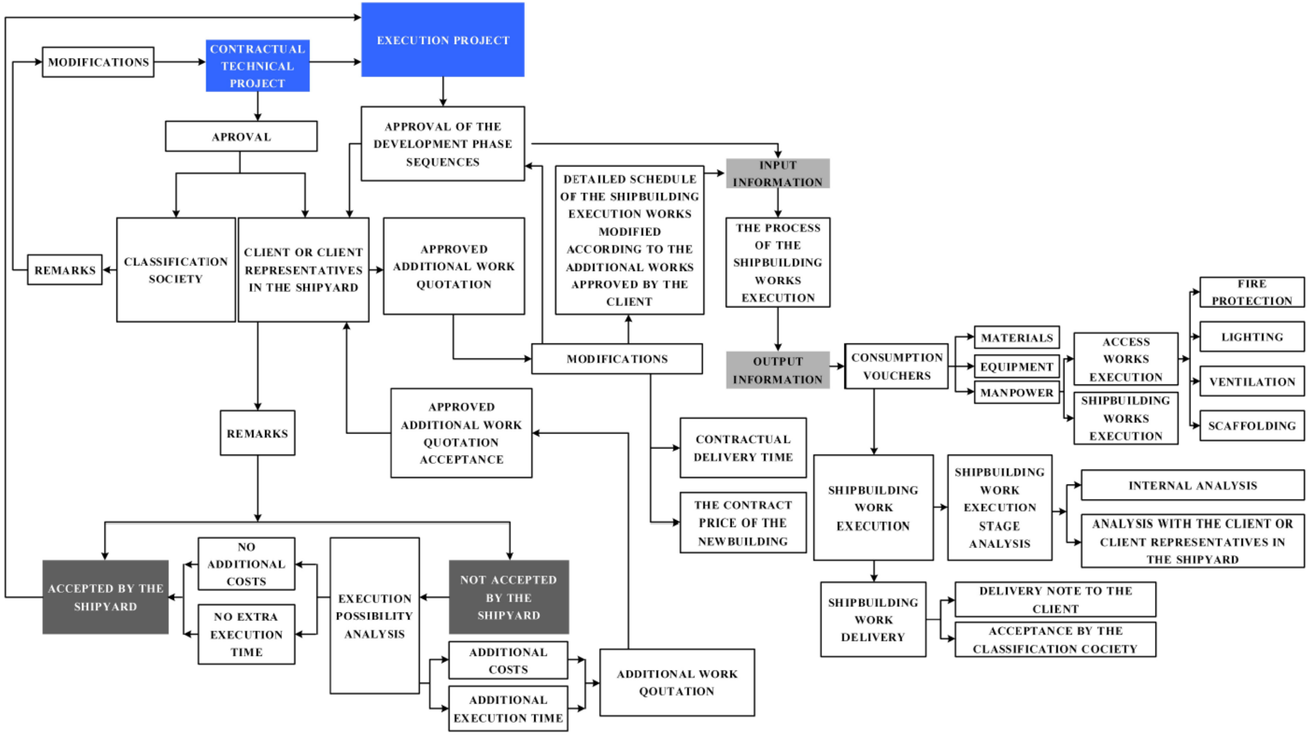
(Manea & Manea, 2023)

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

Construction – Sample Process Execution

Shipbuilding Stages at Constanta Shipyard

Work Execution



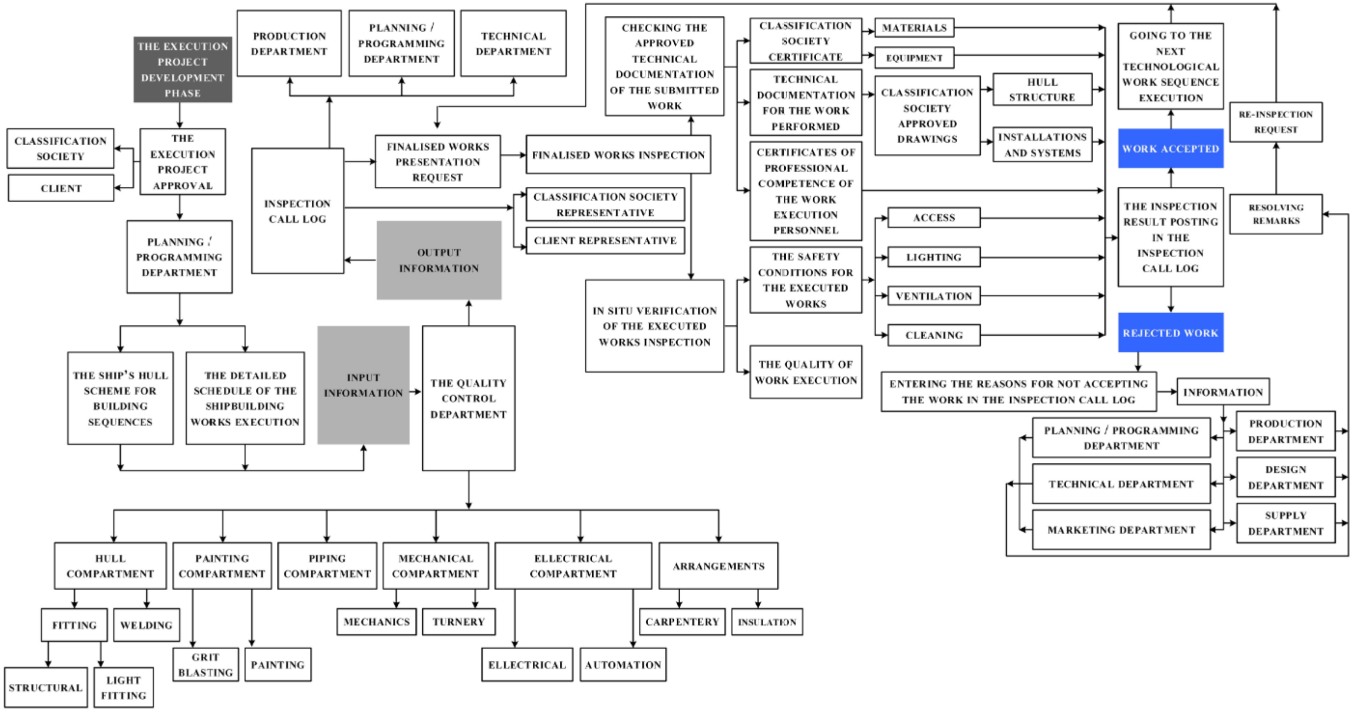
(Manea & Manea, 2023)

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

Construction – Sample Process Execution

Shipbuilding Stages at Constanta Shipyard

Quality Assurance



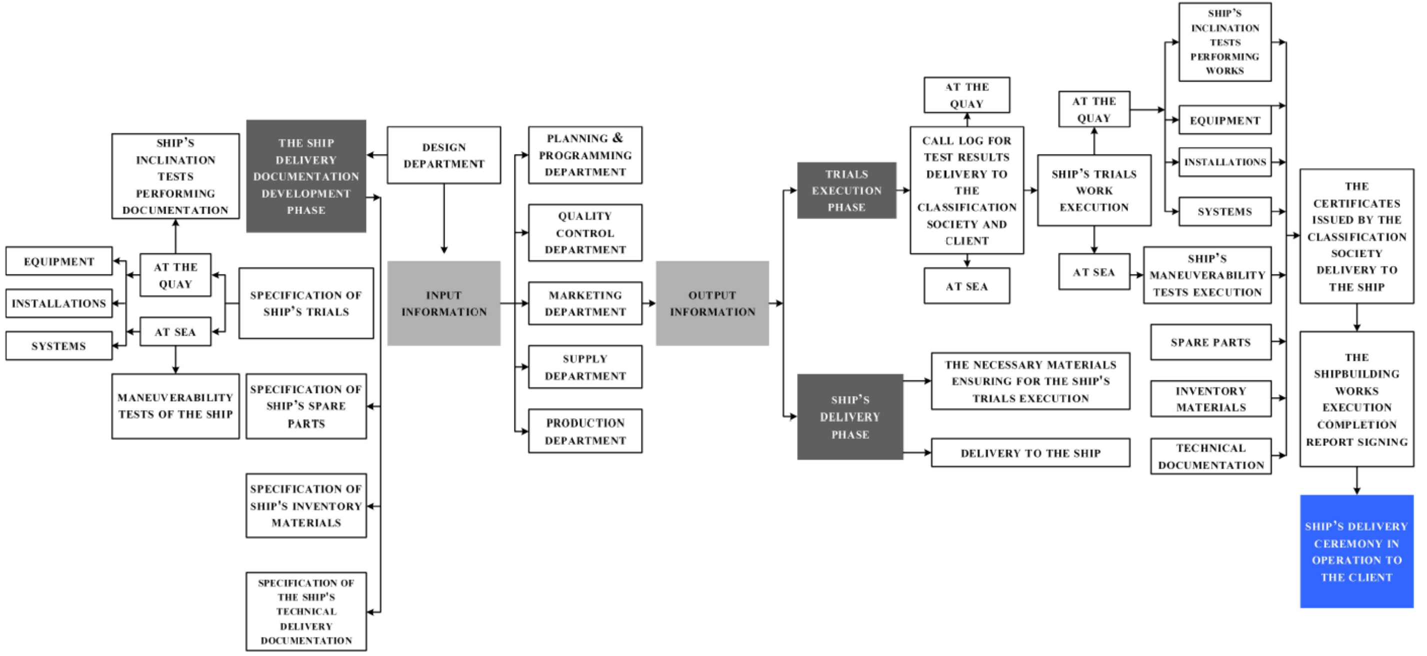
(Manea & Manea, 2023)

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

Construction – Sample Process Execution

Shipbuilding Stages at Constanta Shipyard

Sea Trials and Testing



(Manea & Manea, 2023)

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

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.

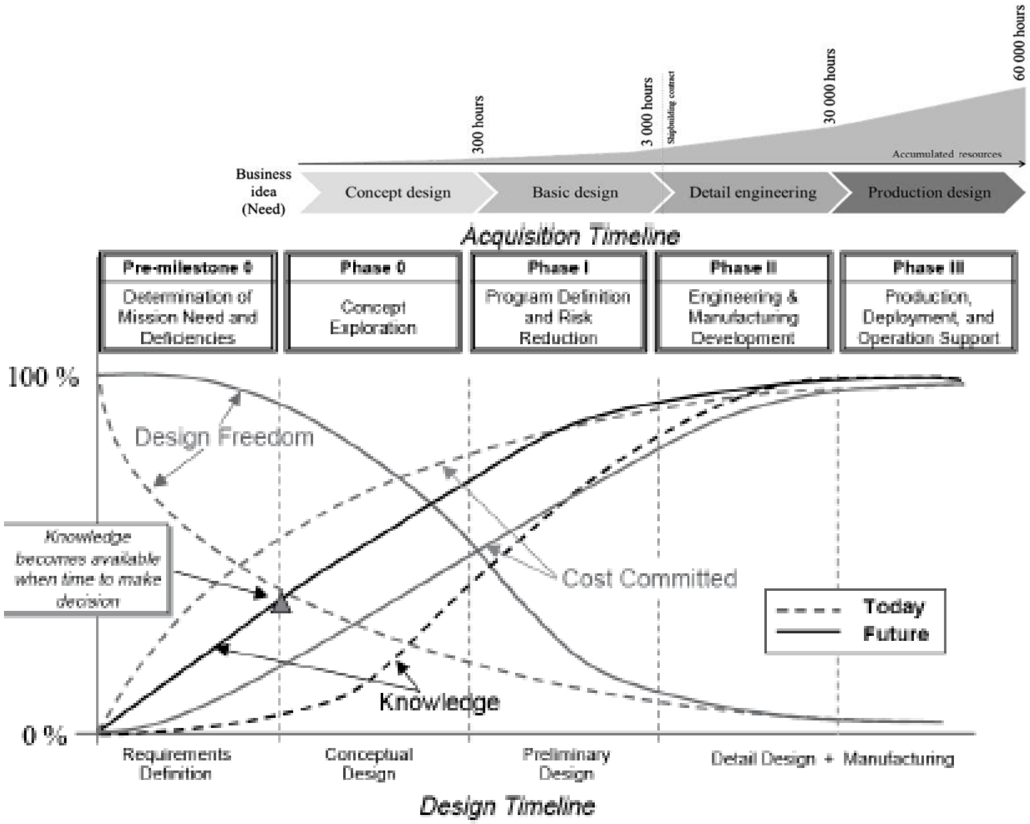
Main Goal of planners: Ensure proper and efficient coordination of parts and materials (with external suppliers and stockyards), proper planning of technicians and staff on the shop floor, and continual liaising with the design team.

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

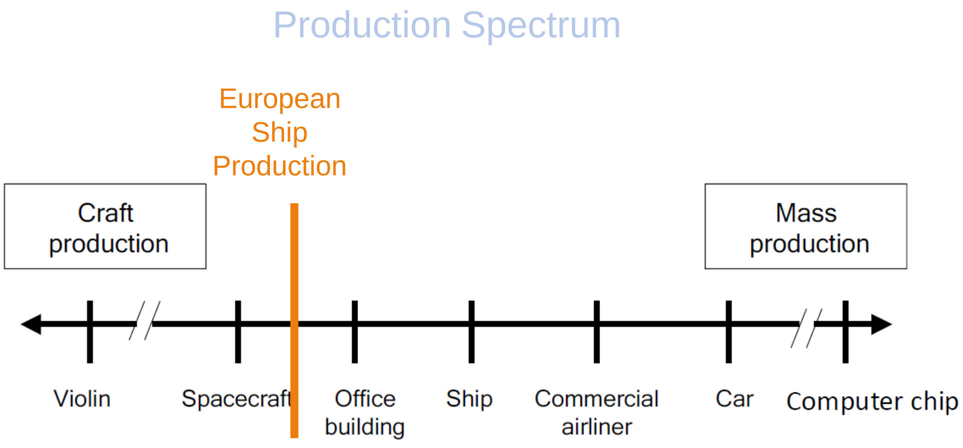
Costs are most heavily influenced at the early stages of the design, when less knowledge is available. Risks are gradually reduced but errors become extremely expensive to correct as the design matures.

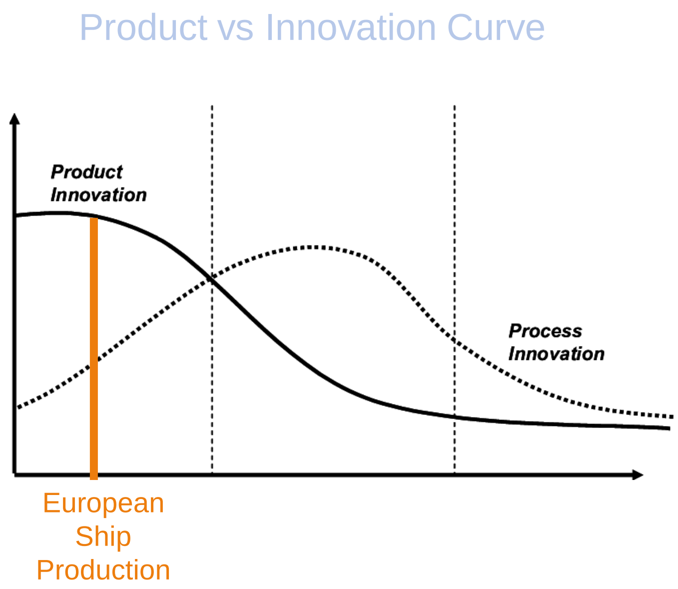


(Shields, 2017), Adopted from (Mavris and DeLaurentis, 2000)

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.





(Koenig, 2019)

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 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

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

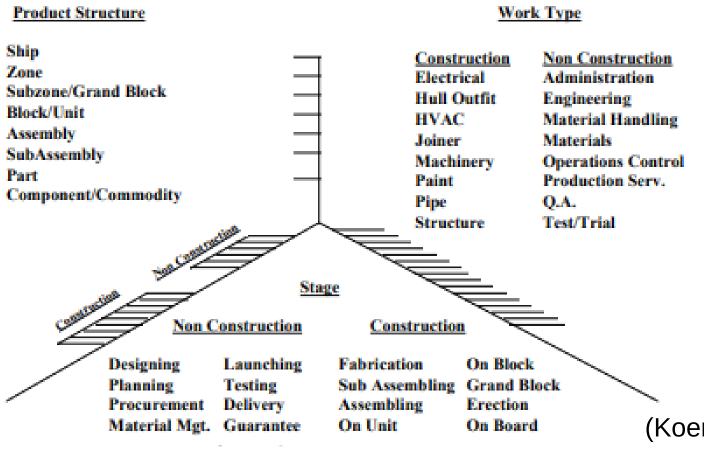
(Koenig, et al., 1997)

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 and by Pal (2015), 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



(Koenig, et al., 1997)

Functional and Systems Ship Breakdown
1960s

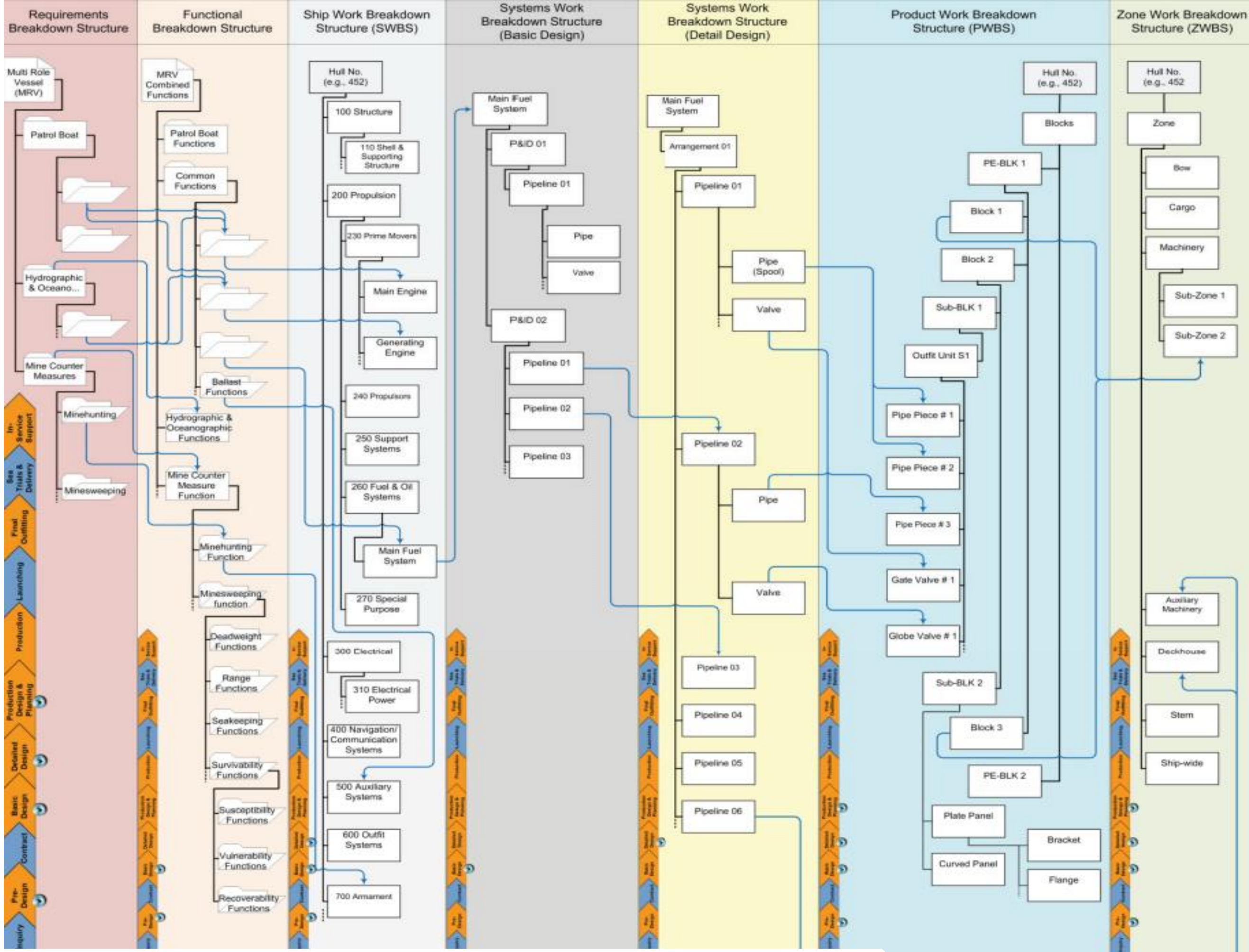
Functional and Systems Ship + Product, Stage, Work Type
1990s

Evolution of ‘**Work Element**’ Definition

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)

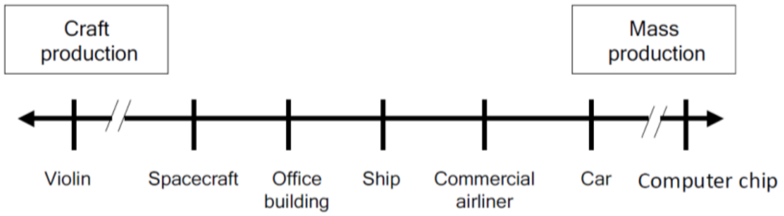


Recall that shipbuilding falls between construction and manufacturing: Construction and manufacturing industries have different 'work element' philosophies. Which philosophy does the ship designer and planner choose?

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

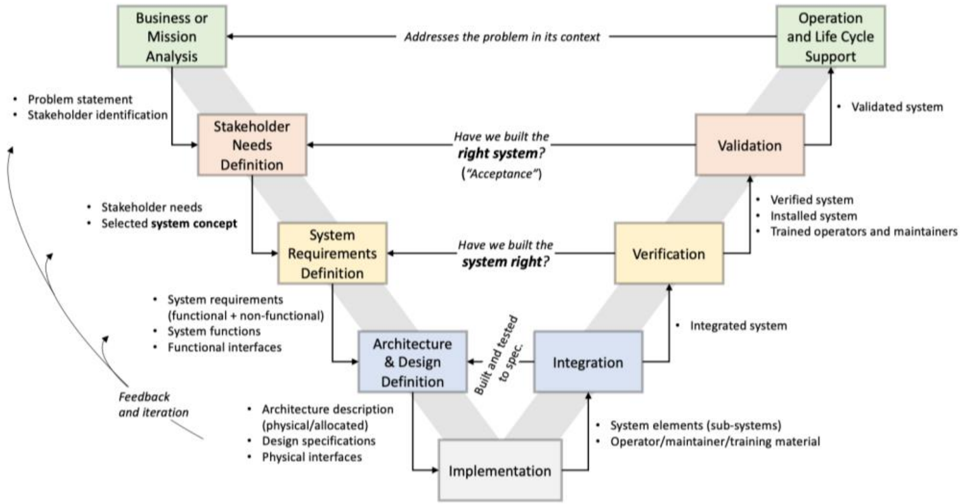
Manufacturing-type industries evolved with a focus on planning units

Intermediate Product Focused

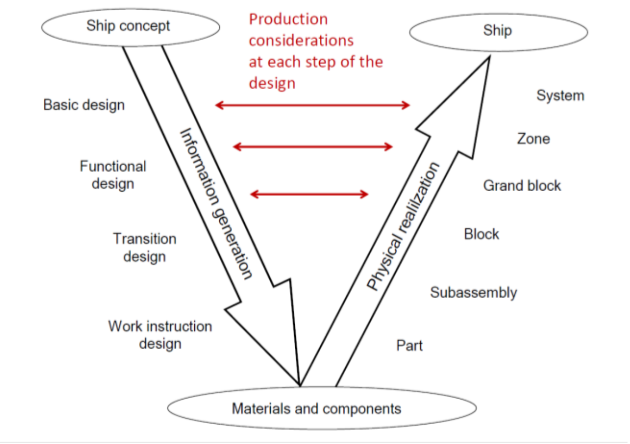
A common systems engineering approach to the definition of work involves the understanding that these work elements evolve throughout the ship lifecycle.

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



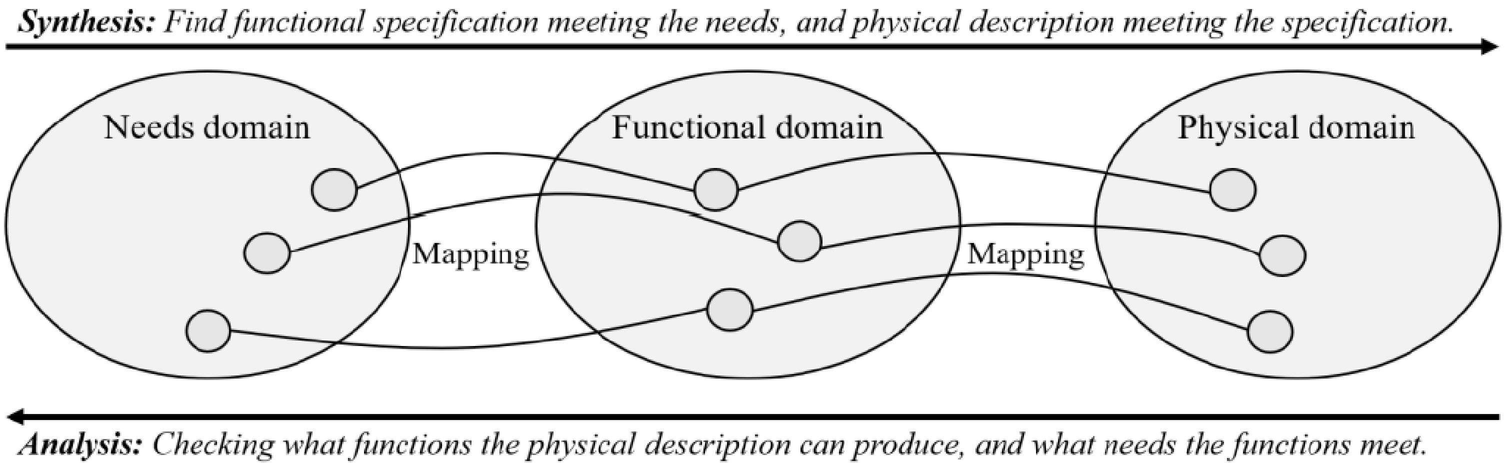
(Koenig, 2019)

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). 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; Pahl & Beitz, 1996; Suh, 1990). Pettersen identified three main domains to consider in ship design.

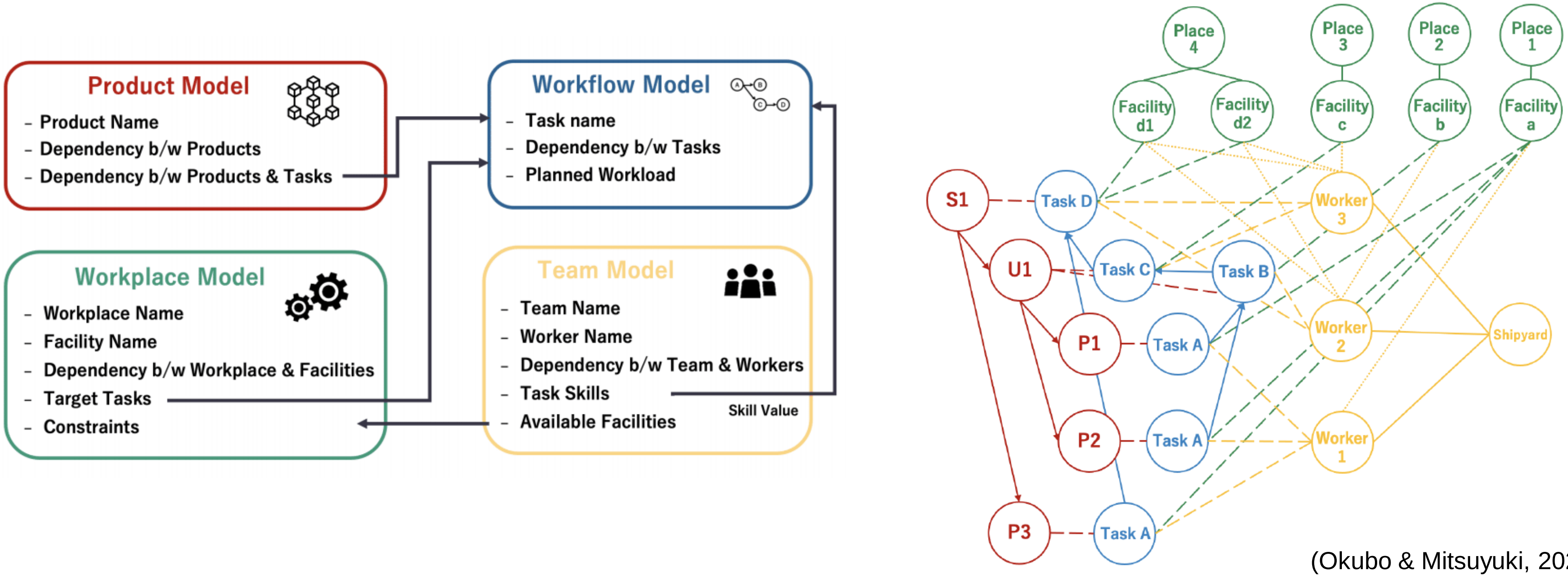


(Pettersen, 2018)

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.

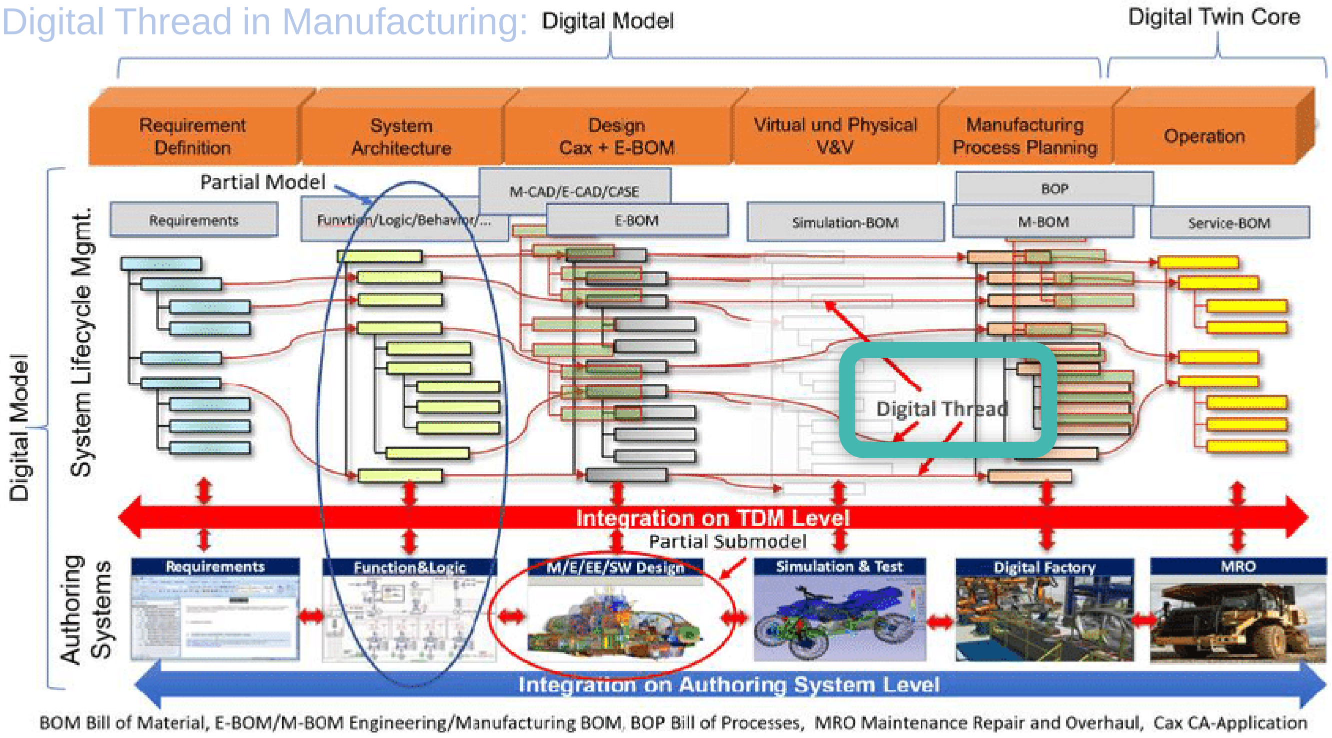


(Okubo & Mitsuyuki, 2021)

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.

Example for Digital Thread in Manufacturing:

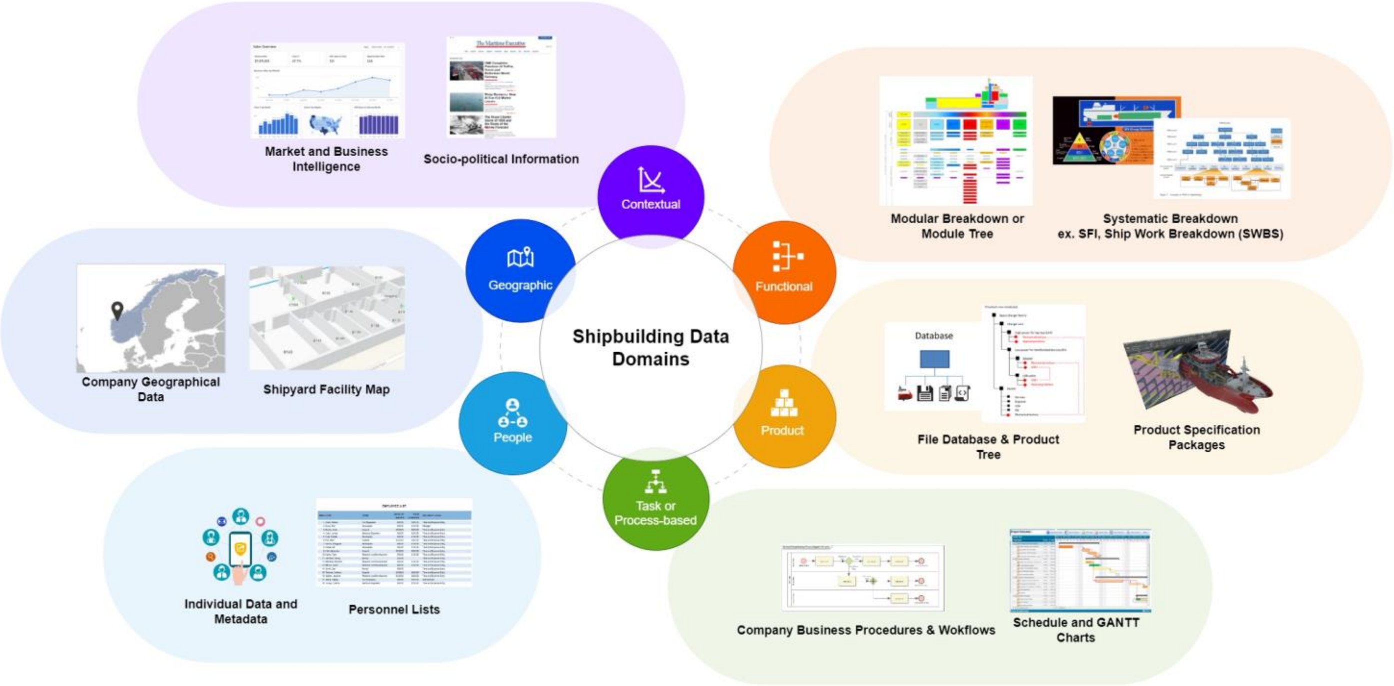


(Eigner, 2020)

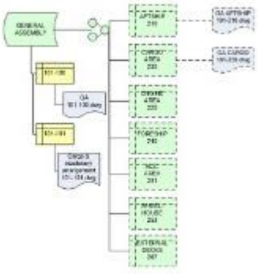
What types of data are required to enable the integration of information and increase ship design traceability throughout the lifecycle?

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

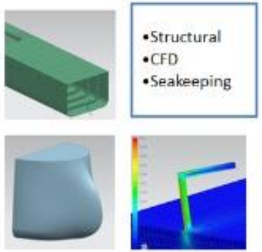
Six Main Domains identified in the SD&SB industry:



Functional Domain

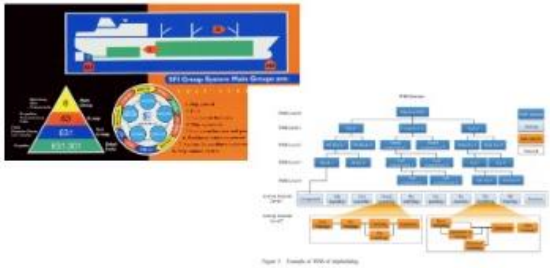


Systems Tree & Library



Functional Analysis

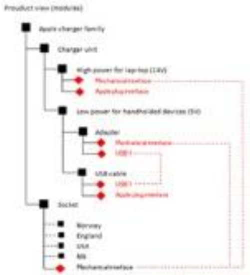
Modular Breakdown or Module Tree



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

Product Domain

File Database

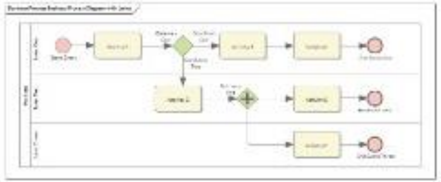


Ship Catalogue

Product Specification Packages

Built Ships

Task or Process Domain




Company Business Procedures & Wokflows

Schedule and GANTT Charts

Shopfloor Task Packages

People Domain

Company Network

Individual Data and Metadata

Personnel Lists

Geographic Domain

Company Geographical Data

Shipyard Facility Map

Heatmap

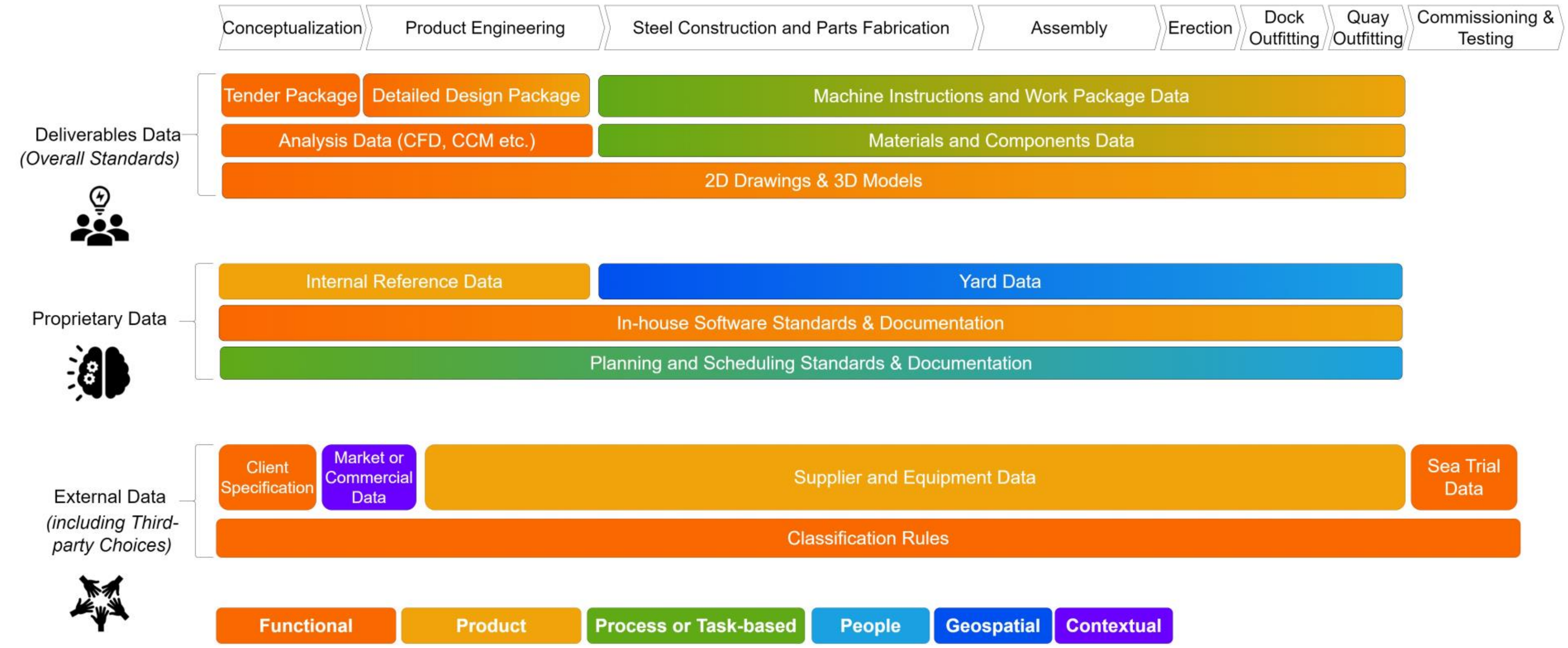
Contextual Domain

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.

upstream value chain

Internal

Classification Society (DNV, BV, ABS)	CAD (NX, AutoCad)	CAE/CFD (NX, Abaqus, model tests, Star CCM)	Suppliers Info (Wartsilla, MAN BW)	Yard Info	3rd Party
Previous Tenders	Previous Designs	Suppliers Data	Yard Data	Sea Trial	Proprietary

(Gaspar, 2018)

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

MEKANISK UTSTYR

Kraner | Vinsjer | Propeller Motorer | etc.

WÄRTSILÄ · FRAMO an Alfa Laval brand · BRUNVOLL PRECISION IS OUR PASSION

ELEKTRISK OG ELEKTRONISK UTSTYR

DP | Programvare | Spesialisert maskinvare | Utstyr for bro | etc.

ABB · KONGSBERG · FURUNO

ANNET DRIFTSUTSTYR

Maling | Smøremidler | Kabler | Kjettinger | Livbåter | etc.

GLAMOX · NORDOX · JOTUN

TEKNOLOGISKE TJENESTER

Klassifisering | Ingeniørtjenester | Teknologisk FoU | Installasjon | etc.

KAEFER ENERGY · DNV

HANDEL

Agenter | Grossister og distributører

FRYDENBØ · pon CAT

DESIGN

Skipsdesign

ULSTEIN · LMG MARIN · WÄRTSILÄ

VERFT

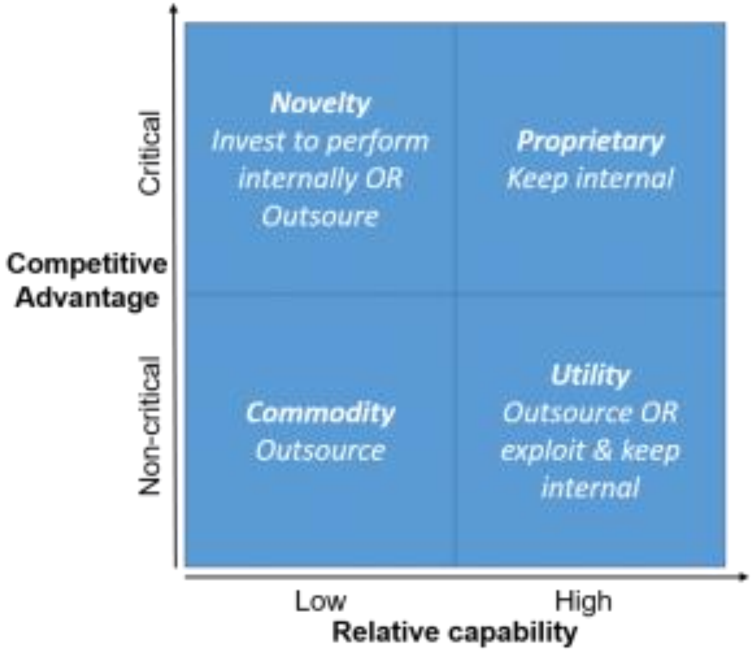
Verft

WESTCON · VARD a Fincantieri company · ULSTEIN

(Menon Economics, 2023)

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)

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

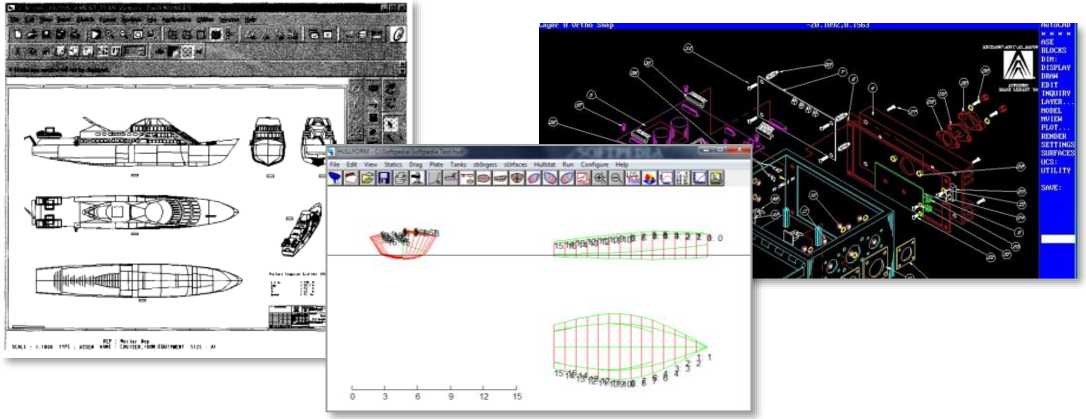
Best Practices on Ship Design and Shipbuilding: Outline

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.

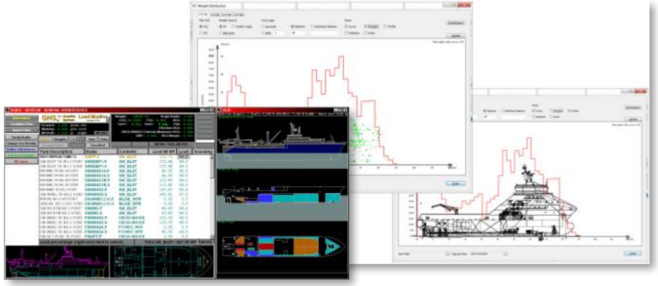
Year	*Hardware*	*Software*	*End Users*
1972–78	Big computing centers, Main frames, Punched cards and alphanumeric terminals	Independent programs, Sequential files, Batch processes	Big shipyards
1979–86	Medium computing centers, Midi/Mini computers, Alphanumeric terminals and graphic terminals	Integrated 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)

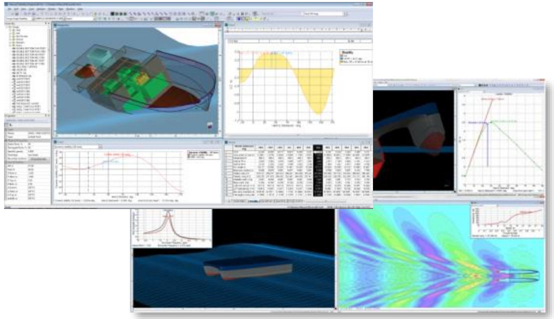


Since the 1980s, CAD (Computer Aided Design) and CAE (Computer Aided Engineering) solutions for ship design have been continuously developed and used to assist with specialized modeling and analysis tasks.

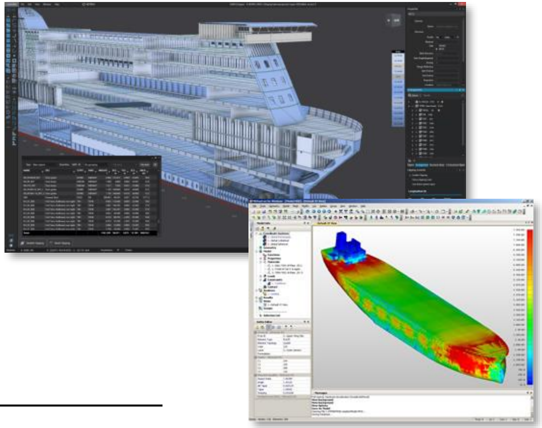
Ship Hydrostatics



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)

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

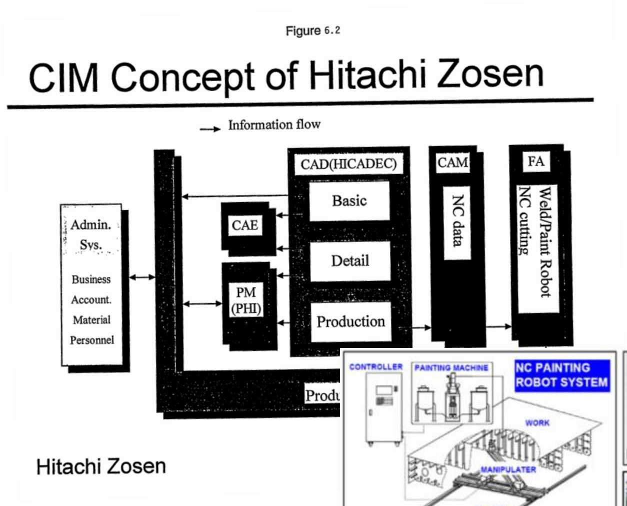
CAE Capabilities

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

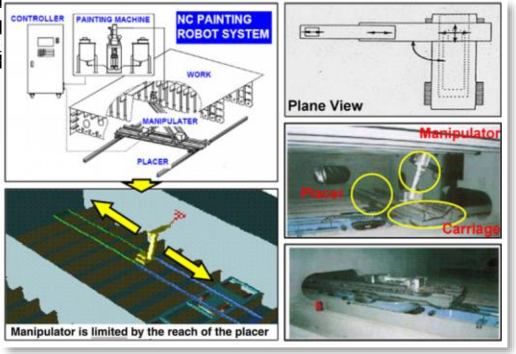
(Ross, 2003)

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

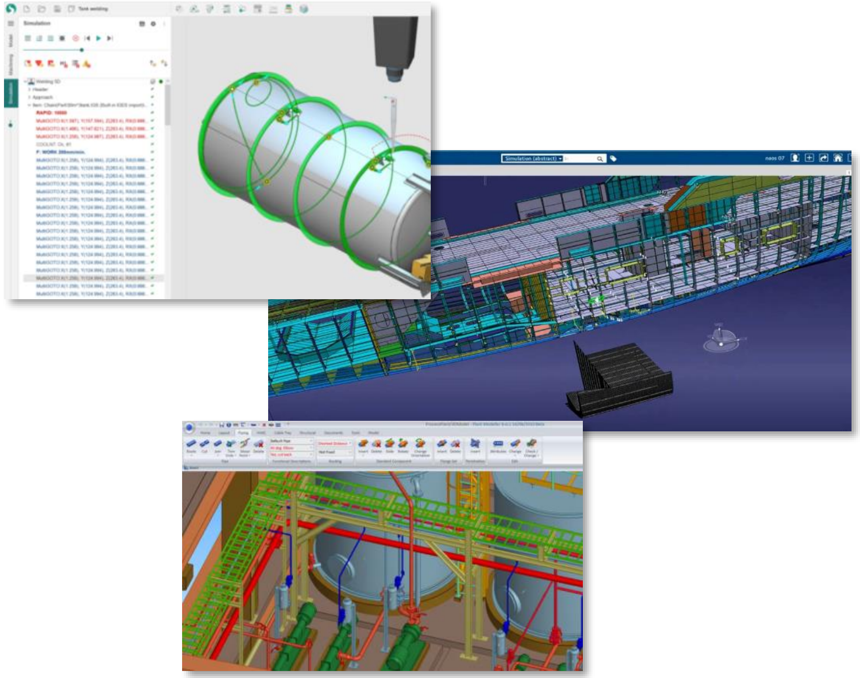


(National Steel & Shipbuilding Co., 1996)



(Ku, et al., 2010)

Current



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

Typical Ship Design CAM Functions:

CAM Capabilities

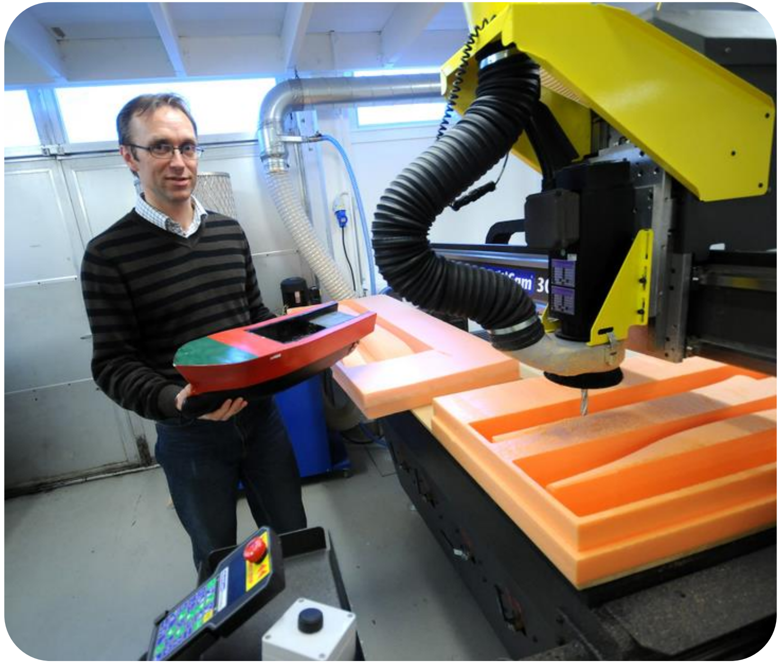
Accounting for weld shrinkage	Paint Design and Monitoring
Dimension Control	Part Coding and Hierarchy
Interface between product model and robots	Nesting
Robotic Programming	Plat and Profile Forming
Production Management Support	Pipe Bending
Lifting Planning	Cable Length

(Ross, 2003)

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.

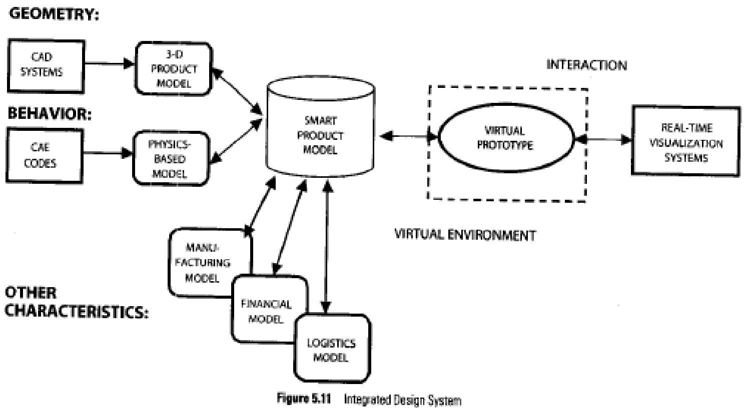
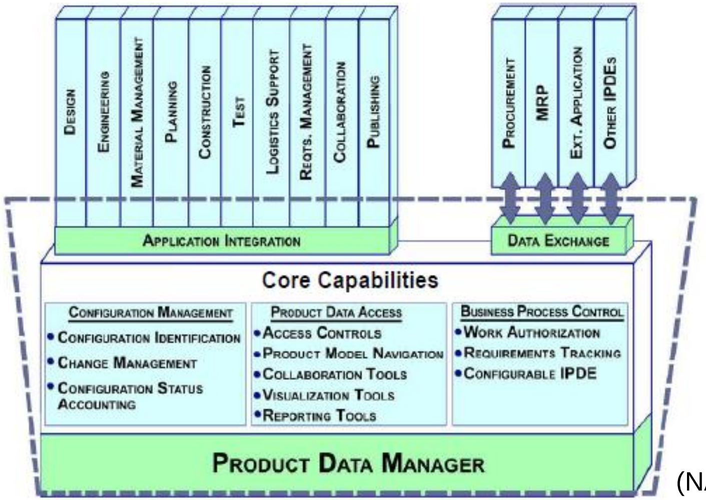


Figure 5.11 Integrated Design System

(Gale, 2003)



(NAVSEA, 2012)

Integration Design System

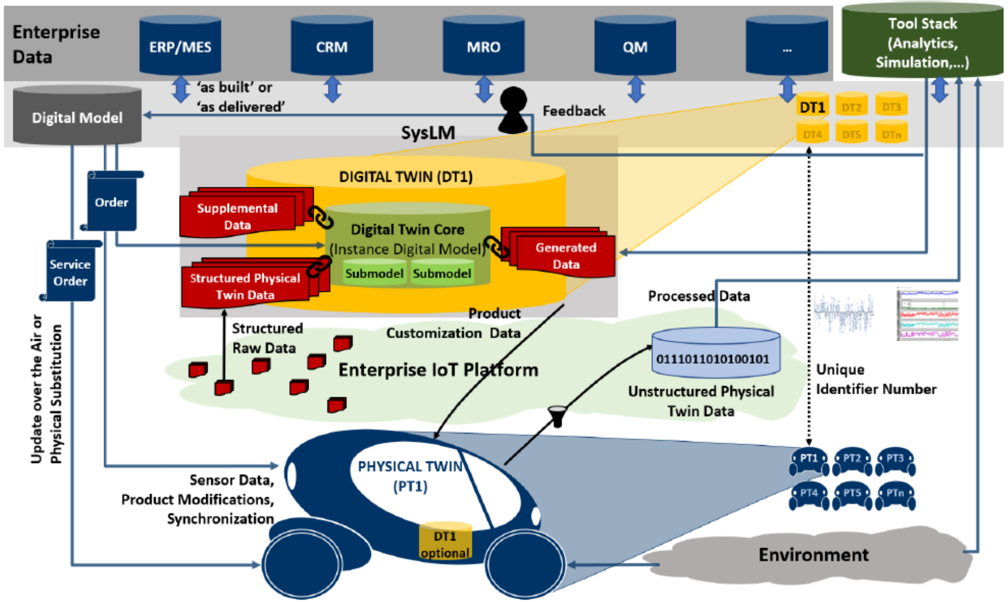
2003

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)

SysML and Digital Twins

Sample Framework for Manufacturing

Evolution of Integration Frameworks

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

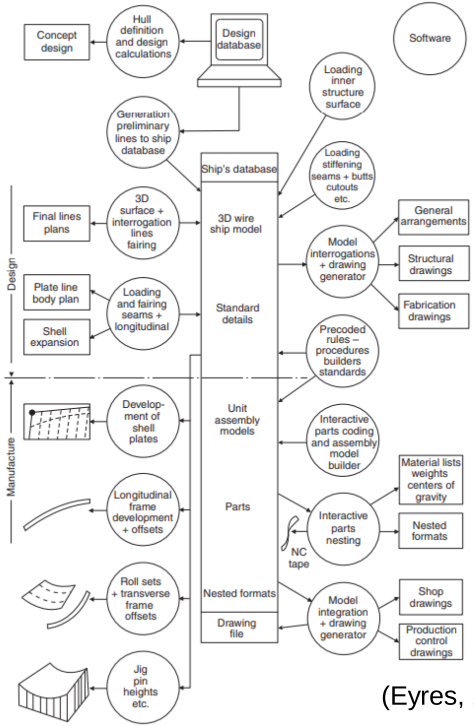
According to Ross (2003), ‘*an important aspect of product definition involves their three-dimensionality. Traditional ship design is carried out in 2D in preliminary stages and extended to 3D in detailed stages. The extension from 2D to 3D results in a large expenditure in time and labor...a product 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)

- Single Integrated Database
- GUI with a consistent format
- Topological relationships among components
- Macros
- Parametric Definitions
- Open Data Structure
- Generation of Structural Penetrations

- Visualization of geometric model
- Build Strategy
- Generation of Drawings
- Nesting
- BoM
- Walkthroughs
- Part Data Libraries

- Hull/Outfit Integration
- Interface Checking
- CAD/CAM
- Multi-user capabilities
- Production Support



(Eyres, 2007)

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

Design: Conceptual/Preliminary Design

1. Concept/Preliminary Design Engineering Analysis Tools
2. Reusable Product Model
3. Develop Initial Build Strategy, Cost and Schedule Estimates
4. Classification/Regulatory Body and Owner Compliance Support

Design: Functional Design

5. Connectivity Among Objects
6. Tools to Develop Standard Parts, Endcuts, Cutouts and Connections

Design: Detailed Design

7. Automated Documentation
8. Detail Design Engineering Analysis Tools
9. Design for Fabrication, Assembly and Erection
10. Linkage to Fabrication Assembly and Erection
11. Automatic Part Numbering
12. Interference Checking
13. Linkage to Bill of Material and Procurement
14. Weld Design Capability
15. Coating Specification Development
16. Definition of Interim Products
17. Consideration of Dimensional Tolerances
18. Context-Sensitive Data Representations

Production: Fabrication Processes

19. Processes to Cut/Form Structural Plates and Shapes
20. Documentation of Production Processes
21. Information Links to Production Work Centers
22. Piece and Part Labeling
23. Creation of Path or Process Programs for NC Machines and Robots
24. Development of Interim Product Fabrication Instructions
25. Simulation of Fabrication Sequences

Production: Joining and Assembly Processes

26. NC Programs for Joining and Assembly
27. Automated Subassembly/Assembly Processes
28. Programmable Welding Stations and Robotic Welding Machines
29. Locations Marking for Welded Attachments
30. Definition of Fit-Up Tolerances
31. Control of Welding to Minimize Shrinkage and Distortion
32. Programming for Automated Processes
33. Definition of Fit-Up Tolerances for Block Assembly Joints

Production: Material Control

34. Capabilities for Material Pick Lists, Marshalling, Kitting and Tracking
35. Tracking of PieceIParts Through Fabrication and Assembly
36. Communication of Staging and Palletizing Requirements to Suppliers
37. Documentation of Assembly and Subassembly Movement
38. Handling and Staging of In-Process and Completed Parts

Production: Testing and Inspection Guidelines

39. Testing and Inspection Guidelines

Operations Management: High-Level Resource Planning and Scheduling

40. High Level Development of Build Strategy
41. Order Generation and Tracking
42. Performance Measurement
43. Production Status Tracking and Feedback
44. Inventory Control
45. High Level Planning and Scheduling

Operations Management: Production Engineering

46. Development of Production Packages
47. Development of Unit Handling Documentation
48. Parts Nesting
49. Development and Issue of Work Orders and Shop Information

Operations Management: Purchasing/Procurement

50. Material Management

Operations Management: Shop Floor Resource Planning and Scheduling

51. Provision of Planning and Scheduling Information to Shops
52. Work Order/Work Station Tracking and Control
53. Detailed Capacity Planning for Shops and Areas
54. Collect and Calculate Costs for a Major Assembly

Umbrella: Umbrella

55. Datacentric Architecture
56. Computer-Automated as Well as Computer-Aided
57. Interoperability of Software
58. Open Software Architecture
59. Accessible Database Architecture
60. Remote Networking Capability
61. Full Data Access (Read Only) to All Project Participants
62. Assignment of Data Ownership
63. User-Friendliness
64. Enterprise Product Model
65. Integration With Simulation
66. Information Management
67. Scalability
68. Transportability
69. Configuration Management
70. Compliance With Data Exchange Standards.

(Ross, 2003)

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

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)

Integrated design practices

Single Source
Tools are able to perform multiple sasks
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.

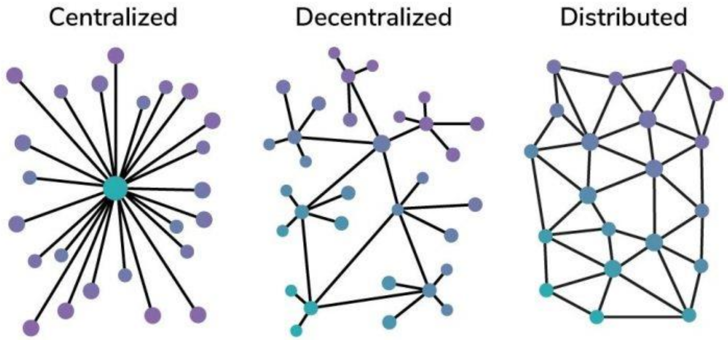
	2D/3D	Level of Detailing	Analysis and Simulation	Integration Capabilities	Data and Handling
2D/3D	2D/3D	Comprehensive models with capacity to filter and extract multiple view points	Model and analysis tools coupled together, with simulation on the go, promising possibility to optimize topology/ arrangement	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 ouputs.	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)

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.

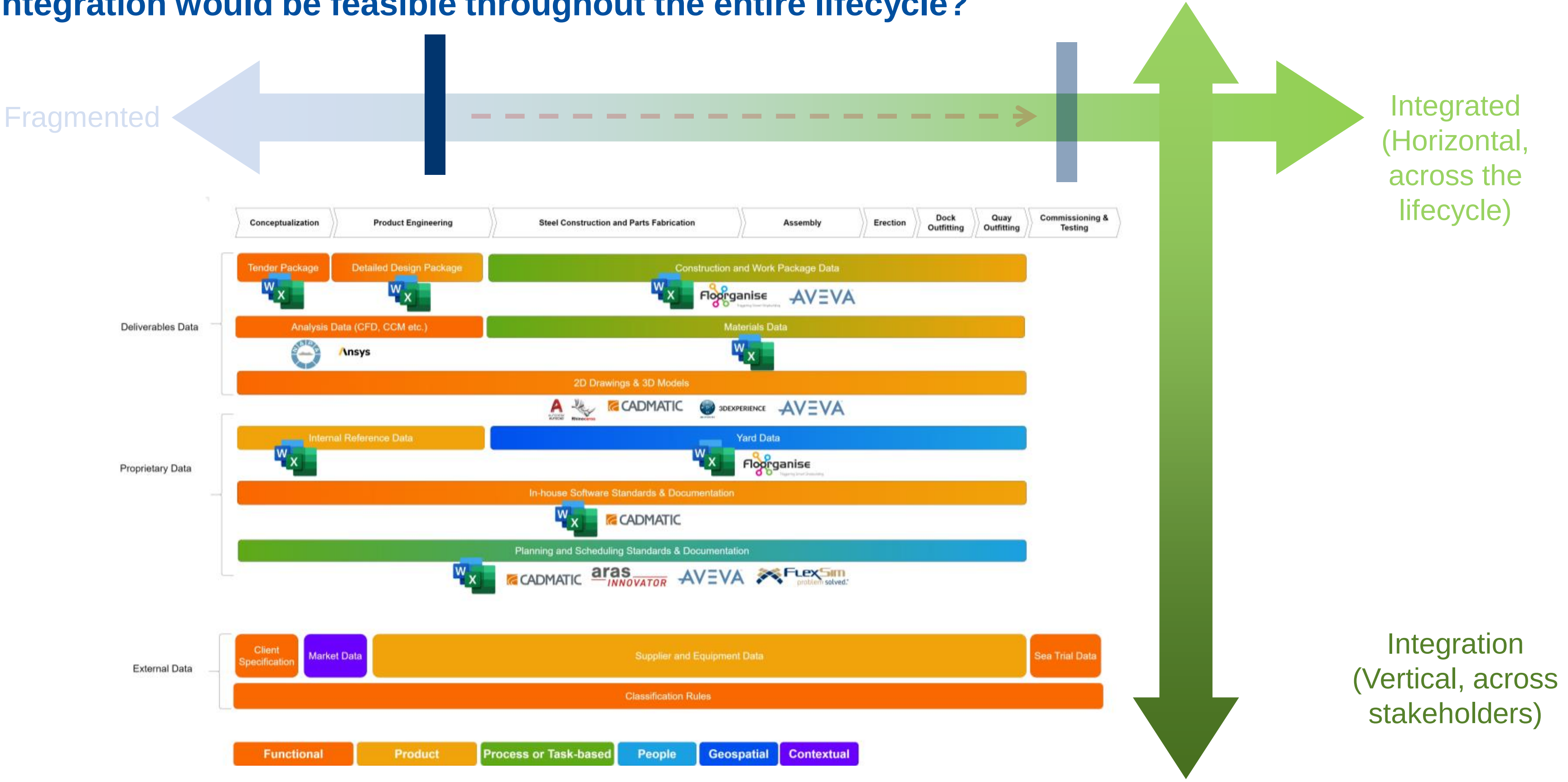
There are pros and cons to the different information systems. For instance, centralization of data allows for easier decision-making and data retrieval. Whereas with decentralization, the risk of single points of failure is decreased.



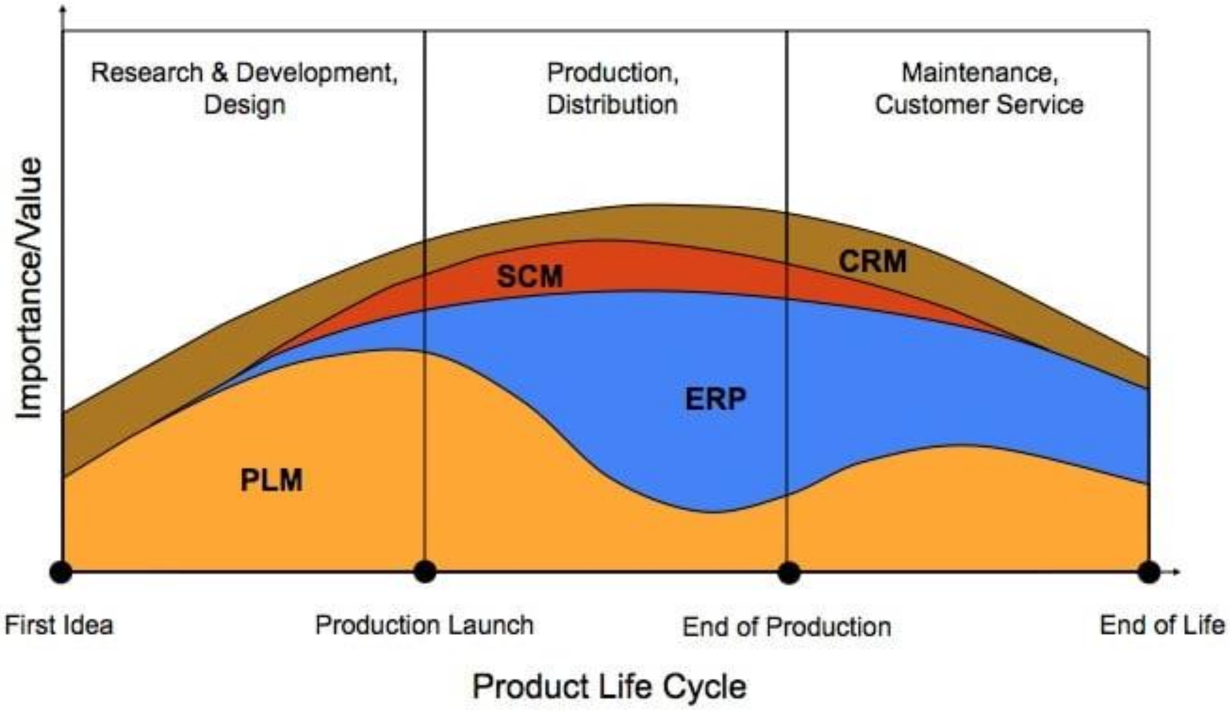
Parameter	Centralized	Decentralized
Control	Users lose ownership of their data as assets are transferred to central servers.	Users retain ownership of their data.
Third-Party Intermediary	A centralized exchange serves as a go-between for the buyer and the vendor. Due to the engagement of third parties, it charges operations fees.	Decentralized exchange serves as a “trustless” platform for transaction authorisation. Transactions are free of middleman fees.
Single Point of Failure	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.
User-Friendly	Beginners will find it simple and intuitive to operate.	Complex, will require education/training.
Anonymous	Centralized networks cannot keep user data anonymous.	Decentralized networks are built on the principle of anonymity.

(Ardana, 2022)

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?



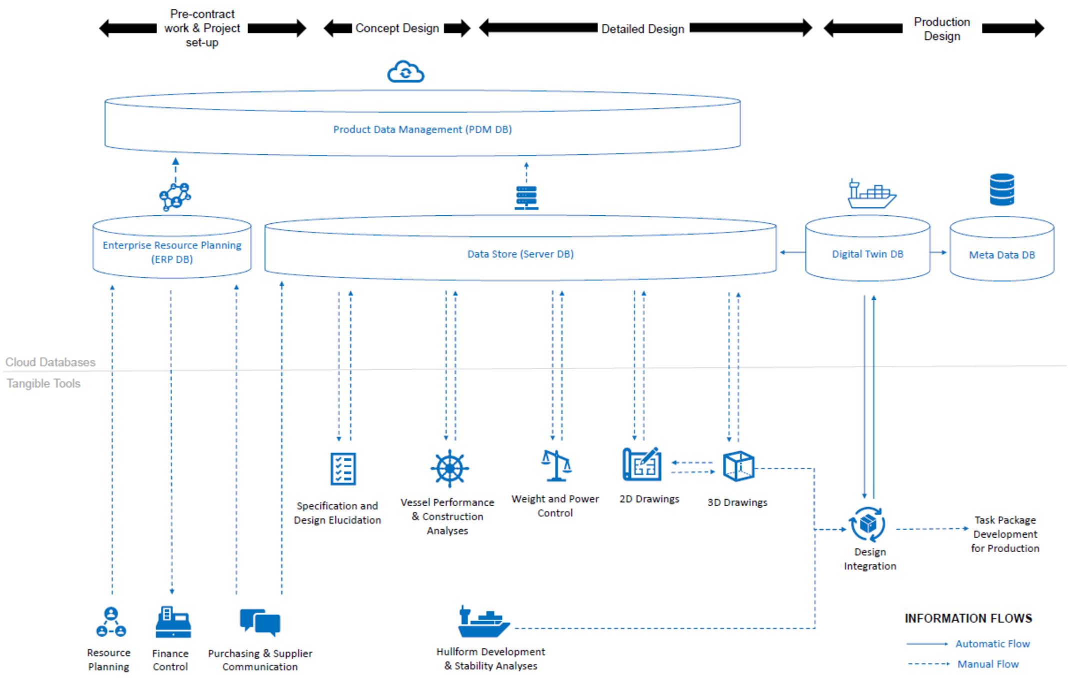
Currently, ship design companies use a combination of various business enterprise solutions to manage these integration needs and enable better planning and resource management. These enterprise tools include Enterprise Resource Planning (ERP) and Product Data Management (PDM).



(Gill, 2018)

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

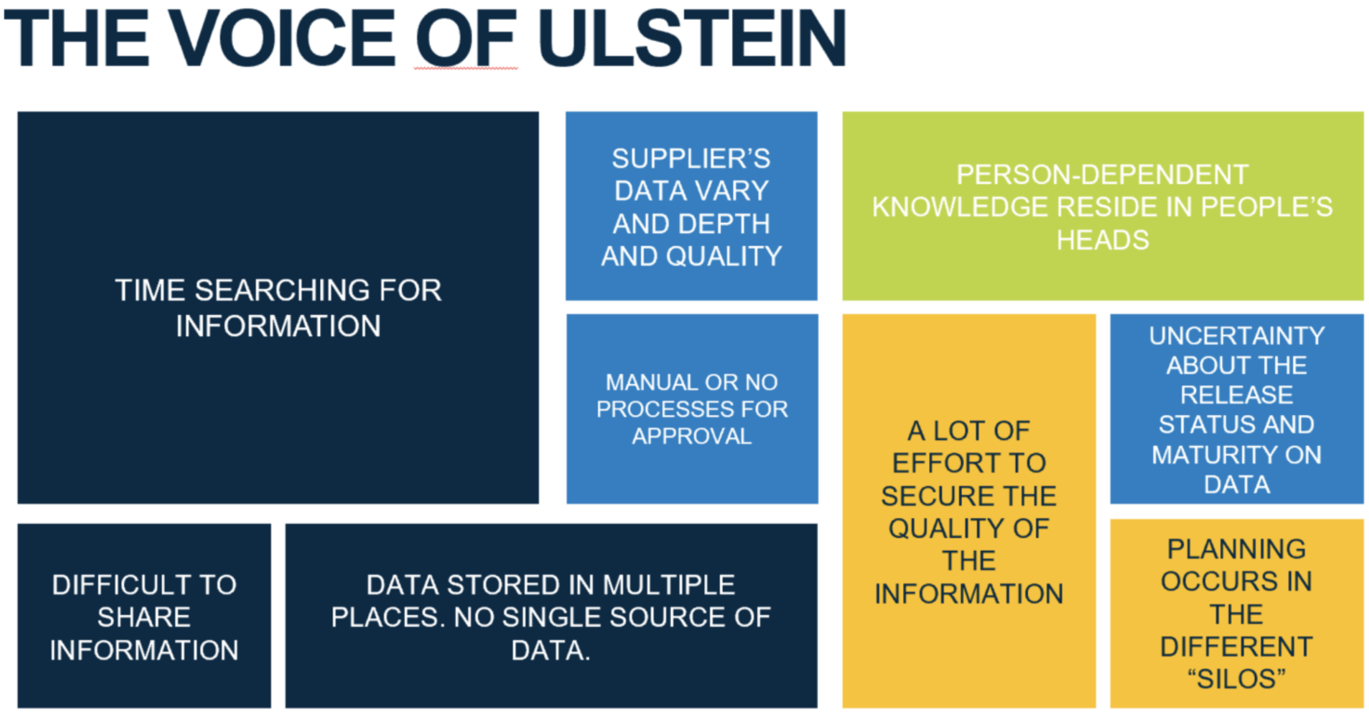
However, these solutions still face common concerns in maintenance and usability, including the lack of automatic information flow processes.



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.



(Vestnes, 2023)

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:

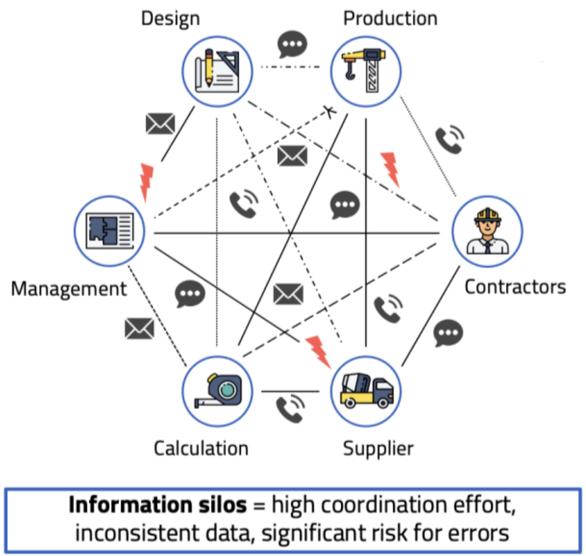
- Unclear degree of integration required (both horizontal across the lifecycle and vertical across various stakeholders)
- ERP and PDM solutions are able to meet limited functions that are bound to a single or only a few lifecycle phases
- Existing tools perpetuate highly disparate information systems
- 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

Best Practices on Ship Design and Shipbuilding: Outline

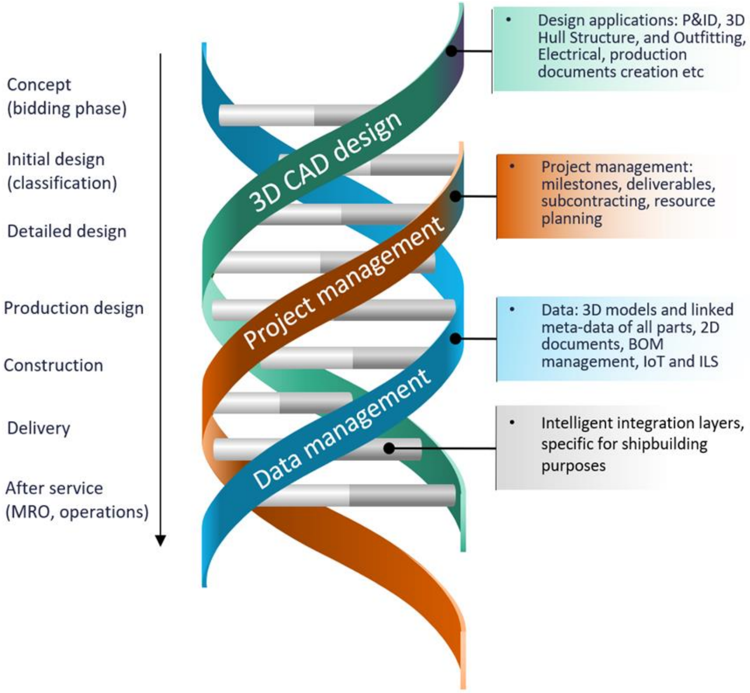
1. EU Shipbuilding and the SEUS Project
2. EU Place in Shipbuilding Market
3. The Ship Design and Shipbuilding Process
4. Multi-domain Taxonomy
5. The Ship Design and Shipbuilding Toolbox
6. **Distinctions in Ship Design and Shipbuilding**
7. Single Source of Truth Concept or Attempt

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

Current



Future

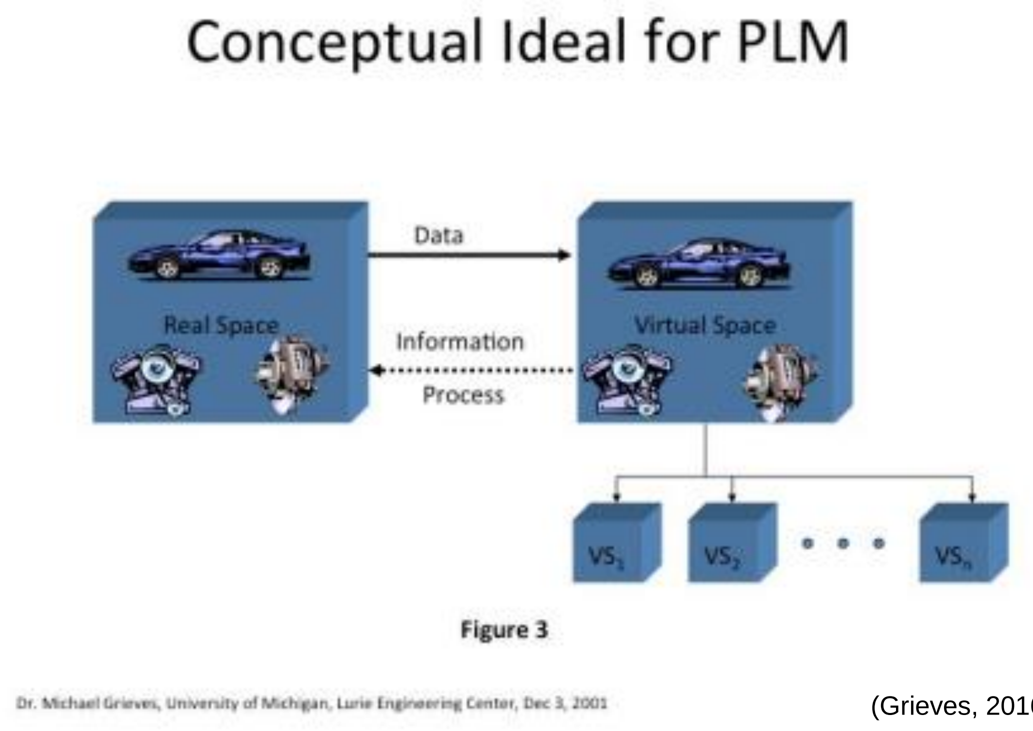


(Naval Architect.io)

(CADMATIC)

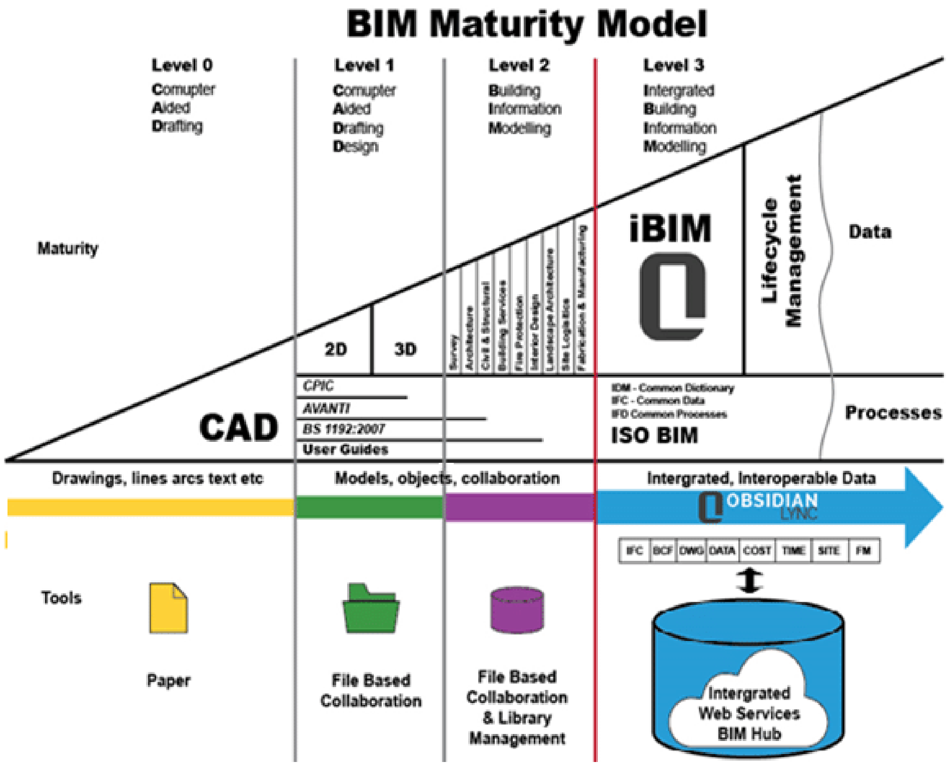
The digital twin trajectory was originally designed to complement Project Lifecycle Management (PLM).

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.



(Grieves, 2016)

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.

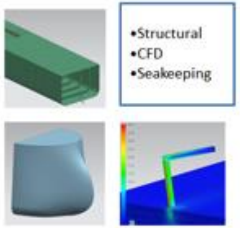


(Barlish & Sullivan, 2012)

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

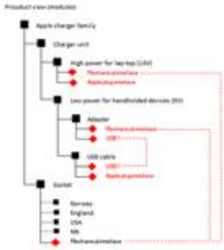
Database

Modelling Tools



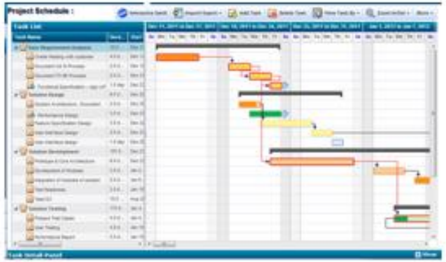
Value Chain Processes

Product Hierarchy



Product Management

Work Processes



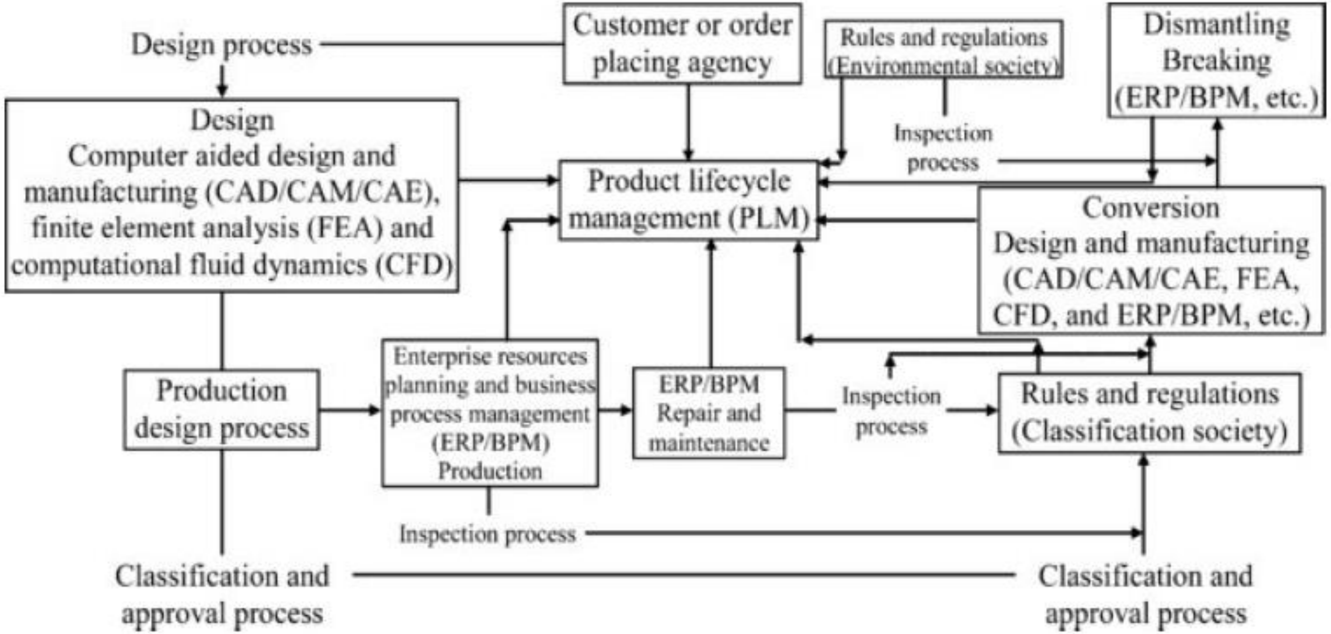
(Andrade et al., 2015)

Hopes for PLM usage in the SD&SB industry:

- 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.
- Promotes a single source of truth
- PLM involves not only control over the design and engineering but also some sort of control over all value chain steps, via:
  - Database: indexation tools and document management
  - Modelling and Simulation: tools, composed of all the software used to design and virtual prototype the vessel
  - Value Chain Processes, management of the lifecycle processes
  - Product Hierarchy: handling the diverse classification ship functions, systems, and components
  - Product Management: administrating all the information related to every physical component
  - Project Management: connecting the processes among the vessel life-cycle

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

PLM Framework

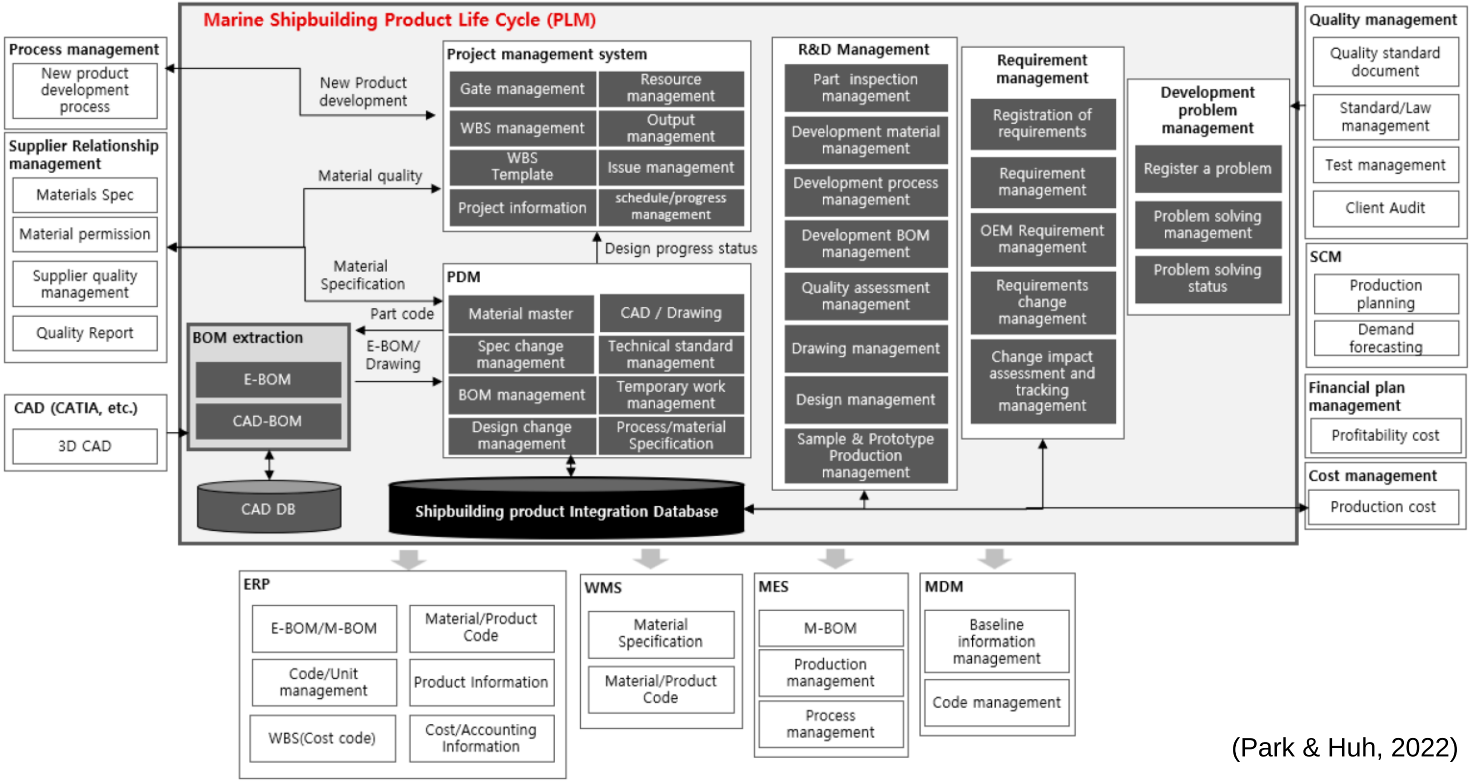


(Sharma, 2010)

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

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

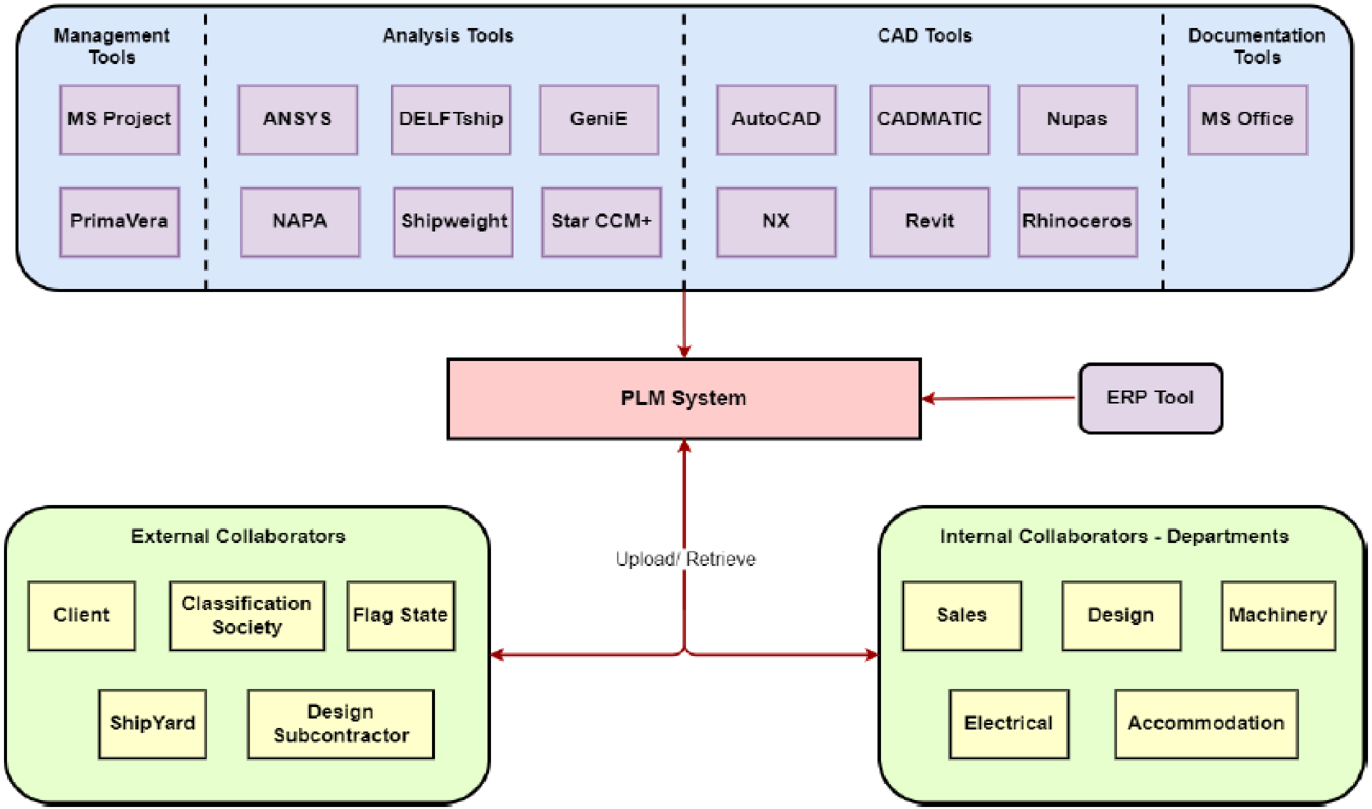
PLM Framework (Sample #1)



(Park & Huh, 2022)

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

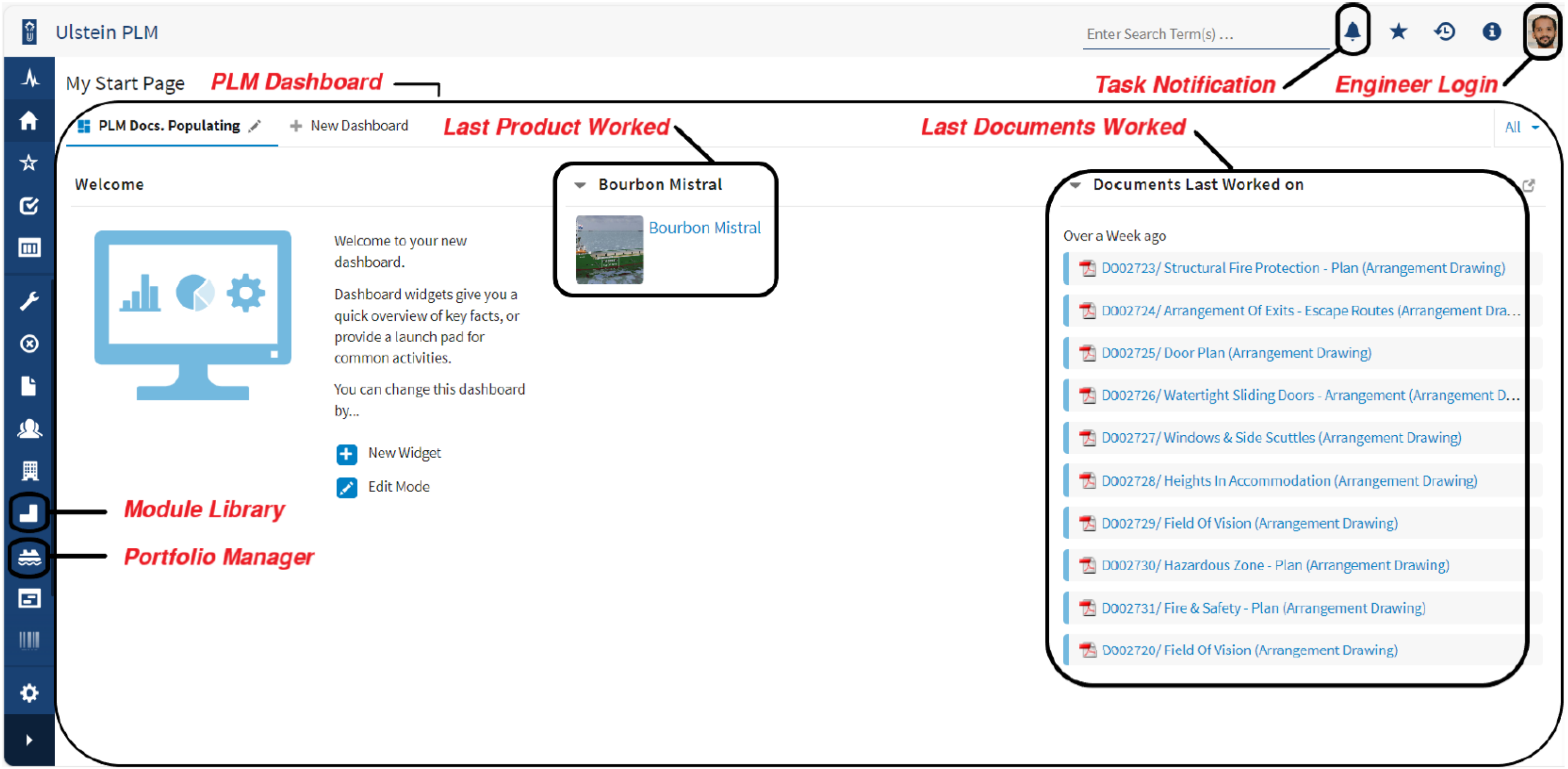
PLM Framework (Sample #2), Ulstein Architecture



(Thamby, 2023)

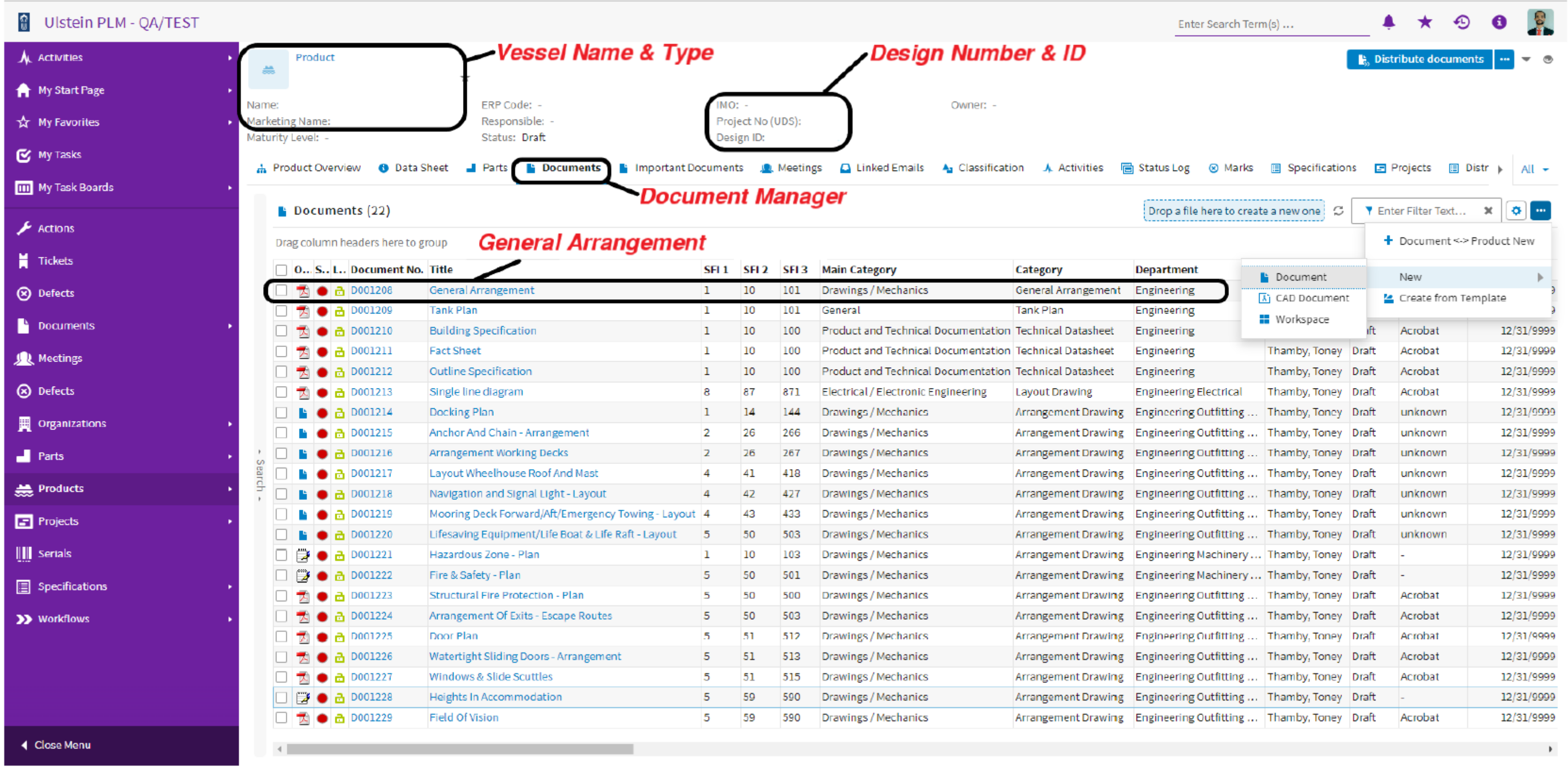
NOTE: These information map is an interpretation of the DMS needs of a company and may vary.

PLM Framework (Sample #2), Ulstein Interface



(Thamby, 2023)

PLM Framework (Sample #2), Ulstein Interface



(Thamby, 2023)

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

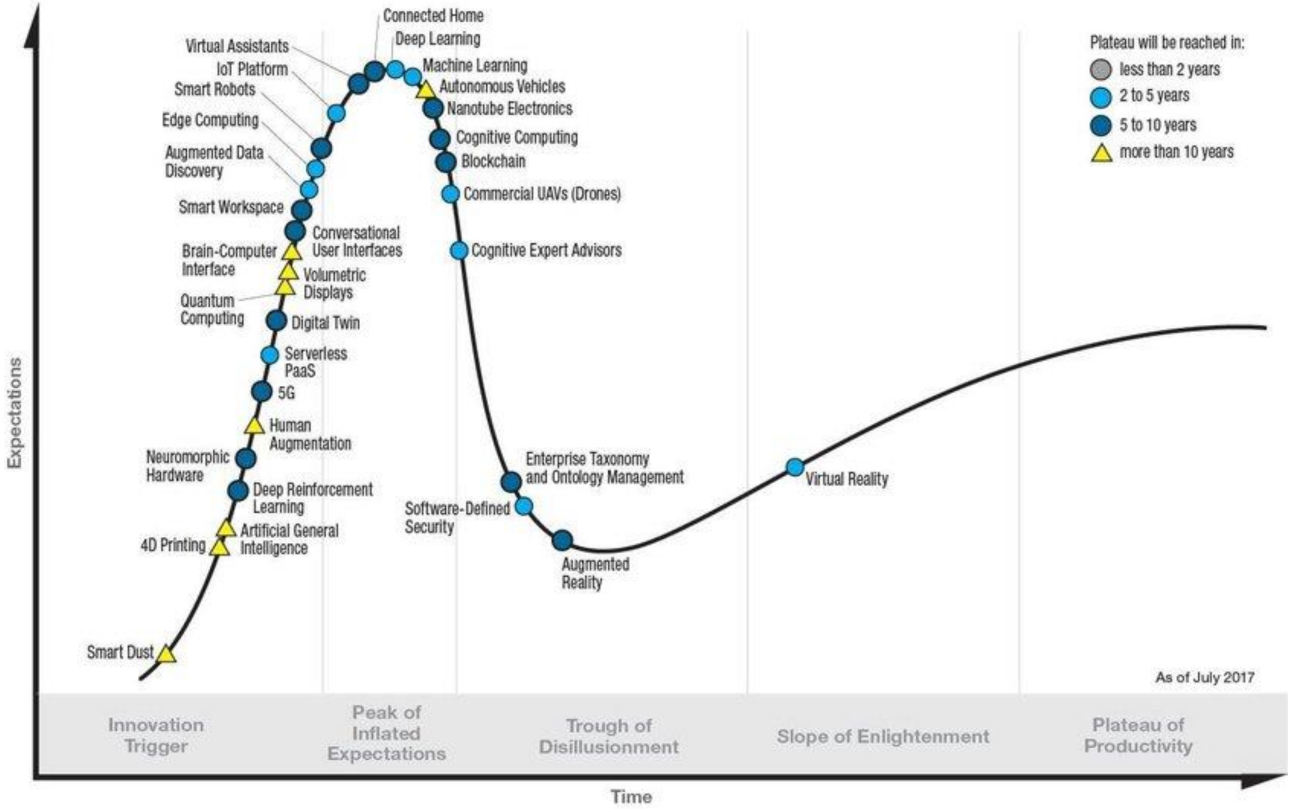
SCM

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

(Hovden, 2018)

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)

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

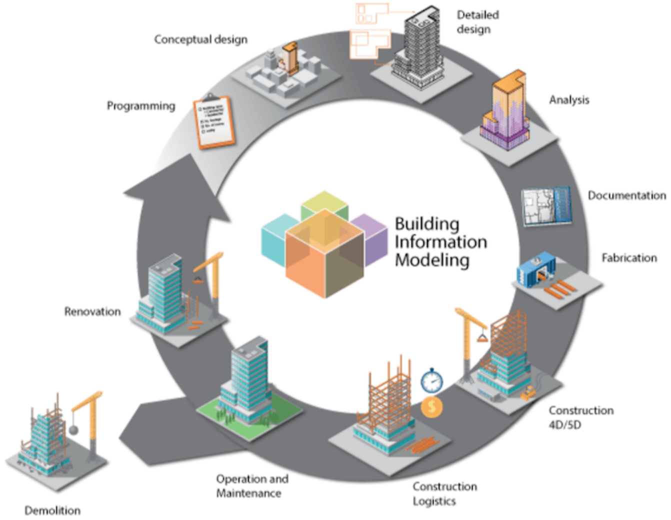
- Re-use and build up on former designs, allowing the designer to fetch former designs from a database, building up new concepts based on the new information
- Re-using advanced 3D models for many value-chain phases (sales, concept, basic, construction).
- Keep the collected and analysed data as accessible 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.

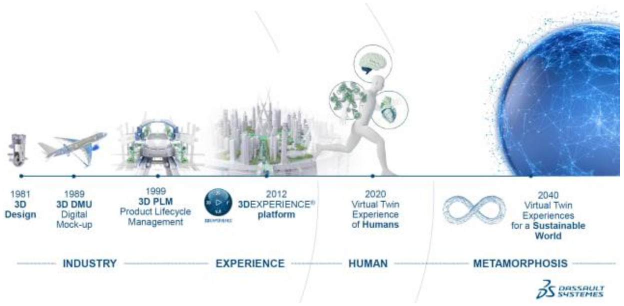
What frameworks and practices from other industries would be worth incorporating to a computational tool/solution for the European SD&SB market?

DevOps & Open Standards

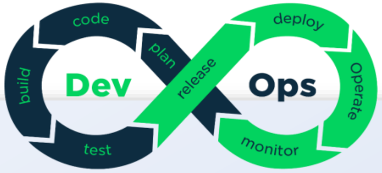
Construction (BIM)

Aerospace (3D DMU)





Transferrable DevOps Elements

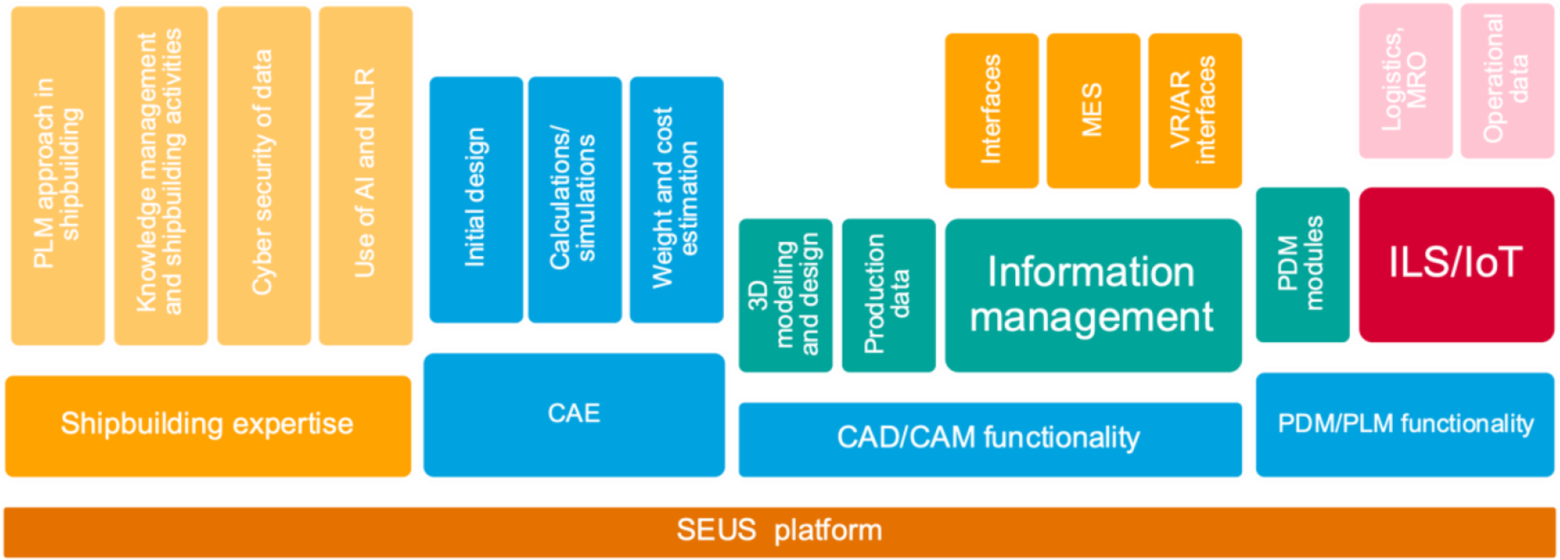


- Data (and code/methods) available to designer and users
- Version control of files and infrastructure to enable collaboration and rollbacks
- Multi-hierarchical data, allowing plural data tags, such as functional/spatial/economic hierarchies, multiples level via *tags* or object properties (main machinery 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

Best Practices on Ship Design and Shipbuilding: Outline

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.



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

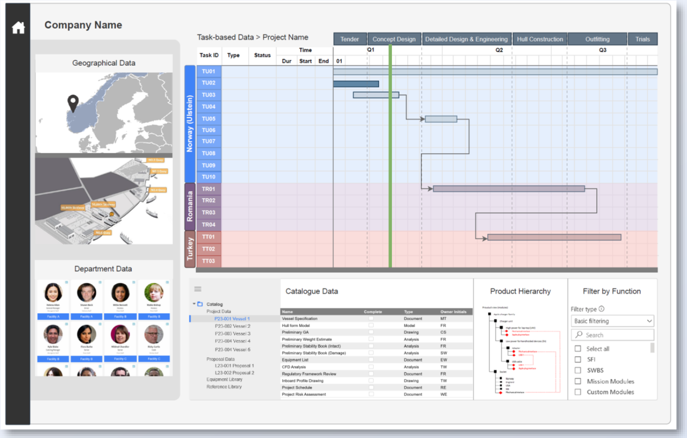
13. How critical is it for you to access data in these domains? (*1 – Applicable* to *5 – Does not apply*)
    a. Functional or Systems-based Data
    b. Product Data
    c. Process or Task-based Data
    d. People or Human Resource Data
    e. Geographic Data
    f. Contextual Data

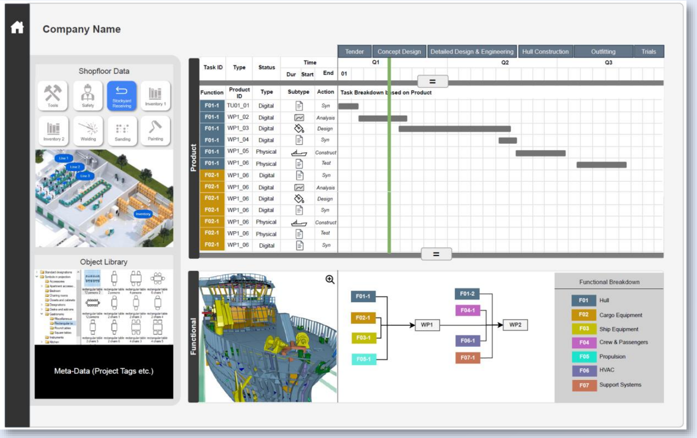
Ongoing Interview

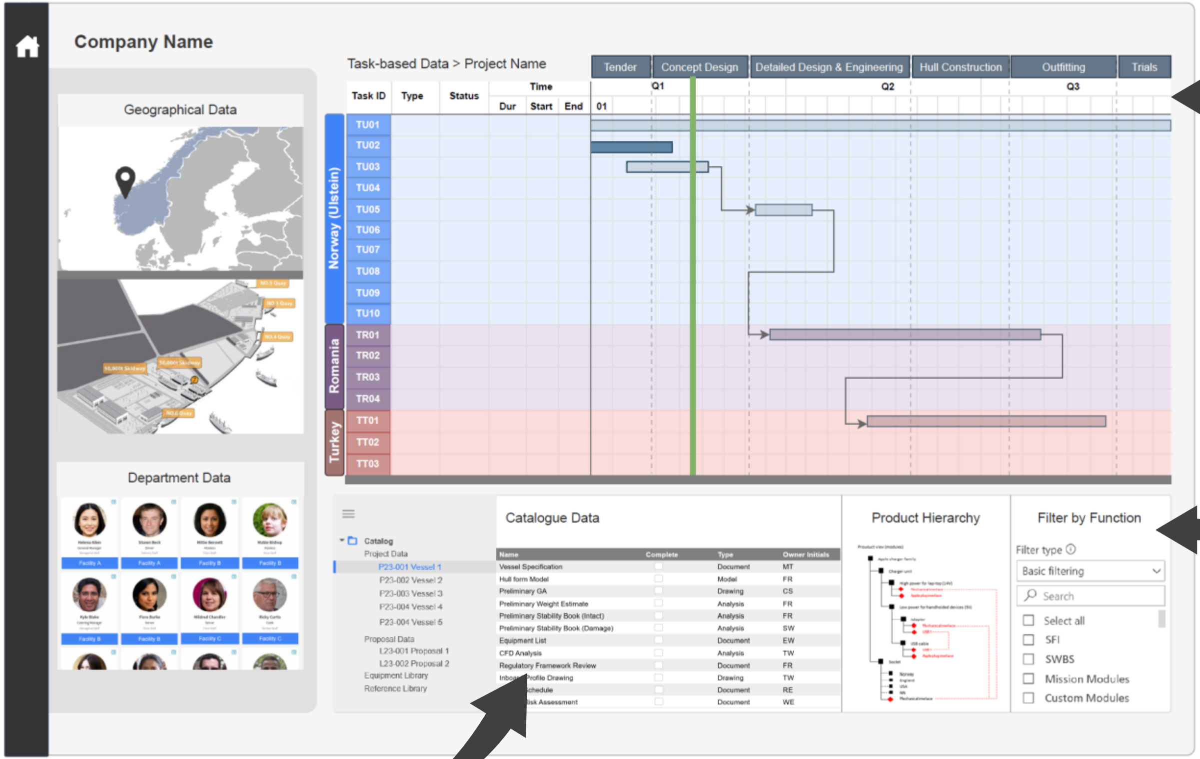
These surveys are also conducted to determine any immediate feedback or preconceptions with a SSoT solution (inclusive of PLM).

Solution-focused Questions

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







Geographical Domain with yard and facilities location

People Domain or overview of team involved

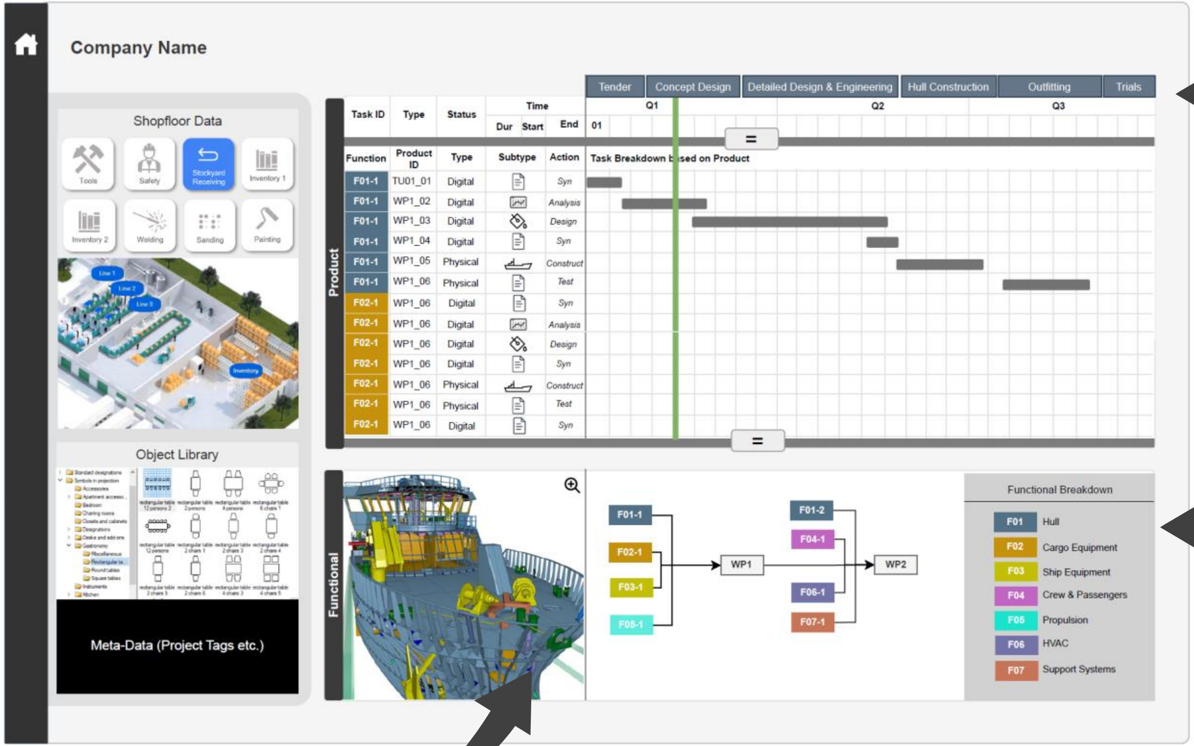
Time Domain across the full lifecycle

Functional Domains used as a filter for other panels

Product or Catalogue Domain filtered by function

Geographical Domain with shopfloor view

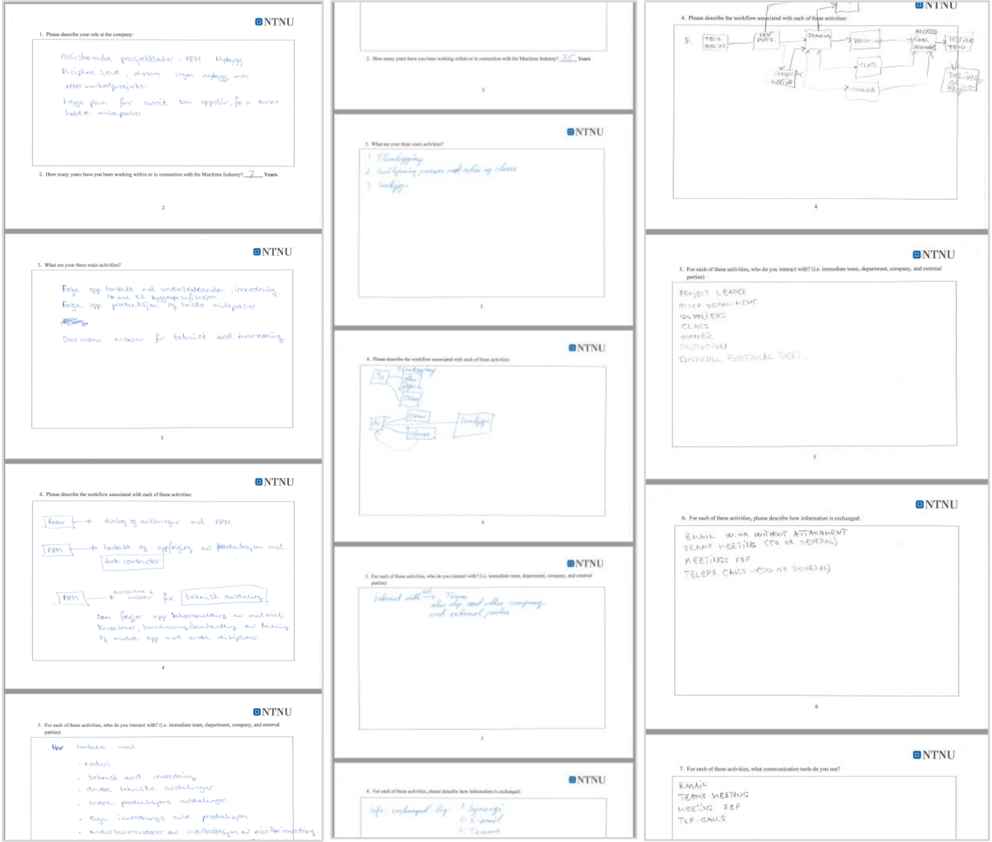
Product Domain presented as an Object library



Time Domain focused on technical completion

Functional Domains represented in terms of relationships

3D Model and Build Simulation Viewer



More to come…

Improved interfaces (aligning better with existing software solutions) to supplement the interviews are underway. Additionally, a more formalized approach to conducting these interviews is being defined.

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[33] 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, 1985)

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