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Advancing Model-Based Systems Engineering in the Development of Naval Vessel Systems Architecture

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ABSTRACT

The increasing complexity of modern naval vessels due to technological advancements poses challenges for early-stage ship design (ESSD). Developing well-defined system architectures and adopting systems engineering approaches are essential to address these challenges. Model-based systems engineering (MBSE) has emerged as a solution to the issues inherent in traditional document-centric methods and is considered the future of systems engineering. This paper aims to address the barriers to MBSE adoption by exploring its value in the early design stage of naval vessels. The paper focuses on system architecture development, covering operational, functional, logical, and physical perspectives, and evaluates two MBSE tools: Capella and CDP4-COMET. The analysis demonstrates that both tools effectively validate anticipated benefits, concluding that MBSE can enhance and accelerate ESSD, with Capella performing better in the early design stages and CDP4–COMET excelling in the later stages. This paper, thus, differentiates itself from traditional performance and detailed design modeling, such as those addressing motion, control, or thermal dynamics.

1 | Introduction

Technological advancements have fundamentally altered the design and operation of modern naval vessels, characterized by interconnected systems, advanced automation characteristics, and versatile mission capabilities. Systems' increasing complexity and interdependence have made them notably harder to comprehend and design, mainly because of the increased potential for emergent properties that only arise once the system is complete and in operation. Consequently, there is an elevated risk of latent errors persisting unnoticed for extended periods, which could lead to catastrophic consequences for the ship [1]. Furthermore, predicting the future requirements of modern warships over their potential 50-year service life is challenging due to the rapid evolution of software-based technology and military capabilities [2]. This complexity underlines the important role of the systems engineering process within ship design, as it offers an approach for effectively managing complex systems.

The systems engineering process is a structured, iterative approach applied throughout all stages of product development to transform needs into system descriptions, inform decision-makers, and guide subsequent development [3]. Developing the system architecture is crucial to understanding, designing, and managing complex systems [4]. This makes it an integral part of the practice of systems engineering. A system architecture formally represents a system that facilitates understanding by organizing relationships, processes, fundamental system components, constraints, and behaviors [5].

Different phases can be distinguished during the vessel's development [6–8]. The early-stage ship design (ESSD) is the first part

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of the ship design process. This primary design stage is crucial for capturing customer requirements and proposing feasible design solutions, which are narrowed down for further exploration. The complexity of this stage, with conflicting information, the need for flexibility, and full traceability to avoid locking in crucial decisions, emphasizes its critical nature [8–11]. This highlights the pivotal role of a well-defined system architecture during ESSD in guiding subsequent decisions throughout the ship design process.

Currently, ship design traditionally still relies on document-centric approaches, lagging behind industries like automotive and aerospace [12]. Traditional document-based methods suffer from precision issues, inconsistencies, and challenges in maintaining and reusing information. Consequently, conventional document-based systems engineering (DBSE) is gradually being replaced by model-based systems engineering (MBSE) as part of the larger digital engineering transformation happening in the industry [13]. MBSE is leading the way and is expected to eventually become a standard practice in the field of systems engineering [14].

However, the industry continues to report significant challenges in adopting and implementing MBSE [13, 15]. Many of these are related to the lack of empirical evidence supporting its value [16]. As noted by Tepper [17], the full potential of MBSE benefits had not been realized in the community as of 2010. Similar concerns persist in more recent studies. Madni et al. [5] investigated the maturity of MBSE, finding that while it showed promise and was increasingly adopted, further advancements were necessary to fully realize its benefits. Although its value had been partially demonstrated, its complete potential had yet to be fully realized. It was concluded that to demonstrate its value proposition convincingly, MBSE needed real-world applications that involved key stakeholders in large-scale projects across various systems of interest. Moreover, Henderson and Salado [16] assessed the empirical support for the benefits and value of MBSE in the systems engineering literature. A systematic review of major systems engineering journals and conference proceedings revealed that approximately two-thirds of the alleged MBSE benefits are based on perceived evidence, highlighting a lack of studies providing measured evidence. Thus, it was argued that most claims about MBSE's value are based on expectations and that the evidence supporting the benefits of MBSE remains inconclusive.

To further add barriers to the adoption of MBSE by the naval industry, it is recognized in the literature that the maritime industry trails behind the state-of-the-art when it comes to advanced digital engineering methodologies, like digital twins and MBSE [18, 19]. Additionally, the traditional ship design process is characterized by the iterative spiral design methodology [20], and traditionally, vessels are based on their predecessors. This reliance on previous successful designs has the potential to derail MBSE adoption, as demonstrated by Zhu and McDermott [21]. It also contributes to the high inertia in the maritime industry, especially regarding the tools utilized, which increases the possibility of further undermining an MBSE integration effort, mainly due to the reluctance of ship designers to adopt innovative designs that require designing a vessel from the ground up to encapsulate the multidisciplinary nature of modern naval vessels.

This paper aims to mitigate some of the barriers to MBSE adoption by practically exploring its value in the early design stage of naval vessels. Specifically, this paper aims to take the first steps in addressing issues surrounding MBSE adoption in other industries, as recognized by Huldt and Stenius [22], namely, the lack of understanding of what MBSE is and its value, and the lack of knowledge and training material regarding its integration. This also aligns with the optimum practices for implementing MBSE van der Ploeg et al. [23] identified, which are essential before focusing on organizational development practices. Within the broader context of ESSD, the scope of the paper is limited to the development of a system architecture encompassing operational, functional, logical, and physical perspectives. The analysis of combinations of modeling tools, methods, and languages for architecting a selected system will deepen the understanding of MBSE's value, provide insights into its practices, and aid in informed tool selection, all from a naval architect's perspective. To achieve this, two MBSE tools, Capella and CDP4-COMET, are evaluated in this research. This paper, thus, differentiates itself from traditional performance and detailed design modeling, such as those addressing motion, control, or thermal dynamics.

A literature review is discussed in Section 2. The section provides an analysis of existing methodologies and challenges in naval ship design, emphasizing the critical phases of ESSD and the pivotal role of system architecture. The literature review continues exploring MBSE and its potential application in naval vessel design, examining its benefits and challenges. These discussions collectively highlight significant gaps in understanding the full extent of MBSE's benefits, its practical implementation, and the tailored application to the specific requirements of naval warship design. The research approach to meet the paper's objective is presented in Section 3. Then, the research process is implemented in a test case mission scenario on an amphibious warfare ship, detailed in Section 4. Finally, Section 5 provides the study's conclusions and recommendations for promising research directions.

2 | Literature Review

2.1 | Ship Design

The ship design process can be divided into distinct phases with specific objectives and outputs [10]. In a naval ship design context, the design process begins with the concept exploration phase, where various design requirements and potential solutions are generated and assessed to identify feasible, relevant, and affordable requirements, as well as key trade-offs and performance factors. Following this, the concept definition phase focuses on fewer promising solutions, incorporating more detailed assessments to ensure they meet the previously defined requirements and mitigate risks [7, 8, 24]. The concept exploration and concept definition phases collectively are known as early stage ship design (ESSD). There are differing perspectives on the precise goals and deliverables of these preliminary phases [7]. Elucidating customer requirements and transforming this information into a viable concept design can be identified as the main objective of ESSD [10].

ESSD stands out as one of the most crucial stages in the vessel's design process [10]. This is explained by the fact that several important and costly performance-related decisions regarding the vessel are made and locked in early in the process. Therefore, it can be easily realized that non-informed decisions and poor designs can lead to significantly raised costs and unwanted consequences [25].

Understanding, designing, and managing complex systems is enhanced through the significance of system architecture [4]. Engineering organizations often start modeling without recognizing that the initial problem statement may not be the best or even right [5, 26]. Neglecting attention to system architecture can result in potential integration challenges downstream [5]. Building incorrect features represents a costly form of waste in engineering development, and engineers often start modeling without recognizing potential flaws in the original problem statement [5]. Specifically, in the ship design process, ensuring that the system architecture is well-defined and effectively meets the stakeholder needs is pivotal. The latter demands that system architecture development must begin at the very early stages of the ship design process [17]. Developing a well-defined system architecture early in the naval vessel design process ensures structure, flexibility, and better decision-making, addressing changes in requirements and reducing risks and costs. However, challenges such as the lack of a universal definition and formalized development process hinder its implementation, making it crucial to establish robust processes for developing system architectures in complex ship design.

The concept of system architecture can be subject to varying interpretations among individuals. In general, systems architecture can provide an effective way to understand, design, and manage complex systems by representing the latter as an abstraction of entities and the relationship between those entities [27, 28]. In this paper, the term "system architecture" encompasses a conceptual model that underlines the structure of a system across four distinct domains. These domains align with the level views used to elaborate and share the architectural model within the Arcadia method [29]. They are also referred to as layers or perspectives:

- **Operational Layer**: defines the problem by capturing what the system users intend to accomplish. It focuses on analyzing customer needs, expected missions, and operational activities.
- **Functional Layer**: describes what functions must be accomplished for the users. It focuses on defining how the system can satisfy the operational needs and the expected behavior.
- **Logical Layer**: describes how the system will work to achieve the expected functions. This perspective aims to build a coarse-grained component breakdown of the system with primary and less likely-to-be-challenged solution decisions.
- **Physical Layer**: describes how the system will be developed and built. Similar to the logical layer, it defines the solution architecture but concentrates on the "final" architecture for system development, implementing technical and technological constraints and choices.

To address the challenging nature of naval design decision-making, it is necessary to explore the fundamental difficulties in this field. Numerous studies have identified and discussed these challenges. The naval design environment is marked by sensitivity to external influences, intricate inter-relationships in sequential design decisions, and the "wicked problem" nature of interdependence between design problems and solutions. Additionally, challenges arise from complex interactions and trade-offs, compounded by limited experience and the novelty of designs. High acquisition costs and the evolving, unpredictable nature of operational requirements further complicate the overall design effort [6, 8, 9, 25, 30]. The authors of these studies underscore the important role of ESSD in the design process, as the majority of costs become fixed by the conclusion of this phase. This paper identifies four key requirements for early-stage design methods for a naval vessel, as follows:

- **Effective decision management**: Design methods should handle dynamic problem dependencies, support transparent decision-making with limited knowledge, and employ a centralized approach to ensure comprehensive, clear, and verifiable requirements.
- **Adaptability to externalities**: Design methods should easily adapt to temporal externalities and evolving requirements to effectively manage uncertainties and trade-offs.
- **Novelty and innovation**: Design methods should promote novelty and innovation, allowing the exploration of unique and creative solutions beyond conventional boundaries.
- **System architecture development**: Design methods should prioritize creating a well-defined system architecture early to enhance coherence, consistency, and decision-making efficiency.

MBSE has emerged as a promising solution for effectively addressing such ESSD method requirements.

2.2 | Model-Based Systems Engineering

Systems engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods [29]. Systems engineering aims to transform needs and requirements into system product and process descriptions, generate information for decision-makers, and provide input for subsequent development stages [3]. It is a proven design approach regularly adopted in naval ship design and defense acquisition projects [3, 7, 10, 31]. The growing complexity of modern combatants has transformed the "Ship Design Process" into a systems engineering process, with ship designers filling both roles and merging the two processes [17].

Future systems must address diverse societal needs and align their life cycles with global industry, economic, and societal trends, while contending with increasing complexities related to safety, environmental impact, security, performance, and human factors [29]. Consequently, traditional DBSE is progressively giving way to model-centric engineering. This shift aims to leverage models, which are more expressive and less ambiguous than documents [29, 32].

TABLE 1 | Mapping MBSE factors to key requirements in ESSD methods.

	Better decision management	Adaptability to externalities	Novelty and innovation	System architecture development
Consistency	X			X
Flexibility		X	X	
Traceability	X			
Trade-offs		X		

MBSE represents a shift in systems engineering practice from document-based to model-based practices. MBSE can be defined as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [33]. Unlike DBSE, which relies on documents, MBSE focuses on domain models as the central source of information exchange [34].

In addressing the implementation of MBSE and the necessary knowledge, Delligatti [35] introduced the popular three-pillar concept, organizing MBSE into three main pillars, namely:

- **Modeling Language**: a semi-formal language that serves as a standardized communication medium, defining the grammar, allowable relationships, and rules for creating well-formed models.
- **Modeling Method**: a documented set of design tasks executed by a modeling team to create system models consistently, ensuring accuracy and preventing variations in scope and depth.
- **Modeling Tool**: a specialized category of software tools designed and implemented to adhere to the rules and specifications of one or more modeling languages.

Several publications have explored the expected benefits of employing MBSE in the early design phases for several industries. However, in the context of ship design, there are notably fewer available publications. While certain studies in this sector remain primarily theoretical in nature [5, 16, 32, 36, 37], others have effectively showcased practical advantages [11, 17, 29, 31, 38–43]. By considering these studies, with a particular emphasis on ship design, MBSE is anticipated to establish a single source of truth, ensure focused attention on system architecture, and enhance decision-making through traceability. Furthermore, it is expected to improve model quality, foster collaboration, and communication, raise early risk awareness and support incremental generation, scalability, and architecture reusability.

Four distinct factors emerge as foundational from the aforementioned benefits: consistency, flexibility, traceability, and improved management of trade-offs. To explore the added value of MBSE in early-stage naval design, a connection needs to be established between the four key requirements for typical ESSD methods and the four expected benefits (referred to as MBSE factors). This mapping is illustrated in Table 1.

- **Better Decision Management**: Achieved through system consistency and traceability, ensuring transparency and verification of decisions against requirements
- **Adaptability to Externalities**: Enhanced by flexibility, allowing quick adjustments, and understanding trade-offs to adapt to evolving factors, as discussed by Zhu et al. [44].
- **Novelty and Innovation**: Supported by flexibility, enabling creative solutions beyond conventional boundaries
- **System Architecture Development**: Relies on consistency, ensuring a coherent and uniform system structure

This mapping theoretically demonstrates that MBSE can meet the four key criteria required in early-stage naval ship design methods, as derived from the literature. Additionally, it guides practical application efforts by defining evaluation criteria, metrics, and evidence to substantiate MBSE's value, ensuring alignment between theoretical benefits and practical outcomes.

Besides the benefits, it is crucial also to acknowledge the limitations and challenges associated with MBSE implementation. Compared to other sectors, traditionally, the maritime industry, particularly ship design, has been less open to innovation due to high capital costs and complex design regulations prevalent in this sector [10, 45]. However, the maritime industry's resistance to adaptation is not the sole obstacle to expanding MBSE practices. Other challenges include high resource demands [13, 32, 34], tool and organizational integration complexities [13], and limitations of current modeling tools [13, 34, 46]. A significant barrier is the lack of knowledge and confusion surrounding MBSE and systems engineering. Stakeholders must be familiar with MBSE tools; without this familiarity, effective adoption and utilization of MBSE are unlikely [13]. Additionally, there is insufficient empirical evidence showing MBSE's value [16]. Lessons learned from those who have practically applied MBSE often serve as the primary evidence demonstrating its value [13].

2.3 | Gap Analysis

Despite widespread positive perceptions, the factors driving the popularity of MBSE remain unclear. This raises questions about its actual value—whether it offers identifiable benefits or is merely perceived as groundbreaking without substantive new contributions [34]. The maritime industry continues to rely on traditional document-centric approaches, lagging behind other sectors in adopting MBSE. This delay is underscored by the lack of empirical evidence demonstrating MBSE's full benefits. Moreover, confusion persists regarding MBSE implementation practices. On top of that, there is a lack of comparative studies that assess how well MBSE tools are tailored for naval ship design. To address this gap, this research explores the value of MBSE in the early design stage of naval vessels. It aims to validate and demonstrate MBSE's benefits in developing systems architecture for naval ships, focusing on operational, functional, logical, and physical perspectives within the context of ESSD. By analyzing industry approaches and two representative modeling tools, this paper provides practical insights, clarifies MBSE practices, and promotes its effective implementation in future naval design projects.

3 | Research Process

This section elaborates on the research approach aimed at assessing the performance of the available software solutions and MBSE methodologies.

The proposed process consists of 10 sequential steps (Figure 1), elaborated below:

1. **Define Mission**: Ensure that the vessel meets its operational objectives. Identify stakeholders, analyze the mission context, and set clear, measurable goals.
2. **Define Capabilities**: Determine the vessel's specific capabilities by creating a capability breakdown. Ensure that priorities align with mission requirements and operational versatility.
3. **Define Requirements**: Derive technical requirements from mission and capability analysis. Ensure each requirement contributes to the mission goals and can be validated for automatic verification.
   Evaluate Sufficiency of Requirements: Check if the requirements are sufficient, aligned with the mission, and enable automated verification for model-based systems engineering (MBSE).
4. **Select MBSE Tooling**: Choose MBSE tools, languages, and methods that align with project objectives. Document the rationale for tool selection to ensure clarity and alignment throughout the modeling process.
5. **Define Metamodel**: Abstract the system of interest (SoI) to ensure a shared understanding among stakeholders. Define essential concepts and relationships that guide decision-making in each design phase. The metamodel serves as a template for system architecture, independent of the selected tools.
6. **Construct MBSE Models**: Develop the system architecture through operational, functional, logical, and physical layers. Iteratively refine the models, revisiting previous perspectives and adjusting the architecture to improve design outcomes.
   Assess Baseline Model Sufficiency: Ensure the baseline model accurately represents stakeholder needs, captures all system requirements, and maintains traceability between different architectural elements.
7. **Verify and Validate MBSE Models**:**Verification**: Ensure the model meets specified requirements and accurately represents the system. **Validation**: Demonstrate MBSE efficacy using built-in or custom rules to ensure adherence to the design strategy.
8. **Modify Models**: Apply predefined modifications to the models, reflecting dynamic changes in system configurations and tool setup. Iterate this process until all modifications are verified and validated.
9. **Collect, Share, and Analyze Modeling Constructs**: Use tools to collect, share, and analyze the developed capabilities of the models.

10 **Evaluate Tools Based on MBSE Factors**: Evaluate MBSE tools using predefined factors, such as:
   - **Consistency**: Automatic validation rules and consistency features.
   - **Traceability**: Requirements verification and traceability features.
   - **Flexibility**: Modification analysis, reusability, and extensibility options.
   - **Trade-offs**: Analysis of design variants to optimize decisions.

4 | Implementation of the Research Process

This paper uses a simple case study to demonstrate how the process can provide valuable insights into the value of MBSE by validating MBSE factors for two different MBSE tools. It is important to note that the case study presented here is fictitious and based on generalized characteristics typical of landing platform dock (LPD) vessels. It does not depict any specific vessel from the Royal Dutch Navy or any other navy, nor does it involve proprietary or classified information. In this section, the setup for a case study focused on amphibious operations using LPD vessels will be discussed. This will include mission definition, capability identification, requirements definition, selection of MBSE tools, metamodel formulation, construction of system architecture models, simulation of dynamic warship design, validation and verification of tools, and systematic assessment based on key MBSE factors.

4.1 | Case Study Setup

This segment focuses on defining the mission, which represents **Step 1: Define Mission**. The case study in this paper demonstrates the key benefits of MBSE using an amphibious naval ship, specifically an LPD vessel, as the system of interest (SoI). It simplifies complexity by excluding interfaces with other fleet vessels and focuses solely on internal interfaces, such as amphibious landing craft, aircraft systems, and personnel, including the amphibious task force and ship crew (all onboard personnel). An amphibious raid is selected as an illustrative example mission from the range of amphibious operations. The main objective of the amphibious raid mission is to ensure the embarkation and safe transportation of the Amphibious Force (AF) and their equipment from the base to the drop-off point while maintaining ongoing support throughout the assault phase

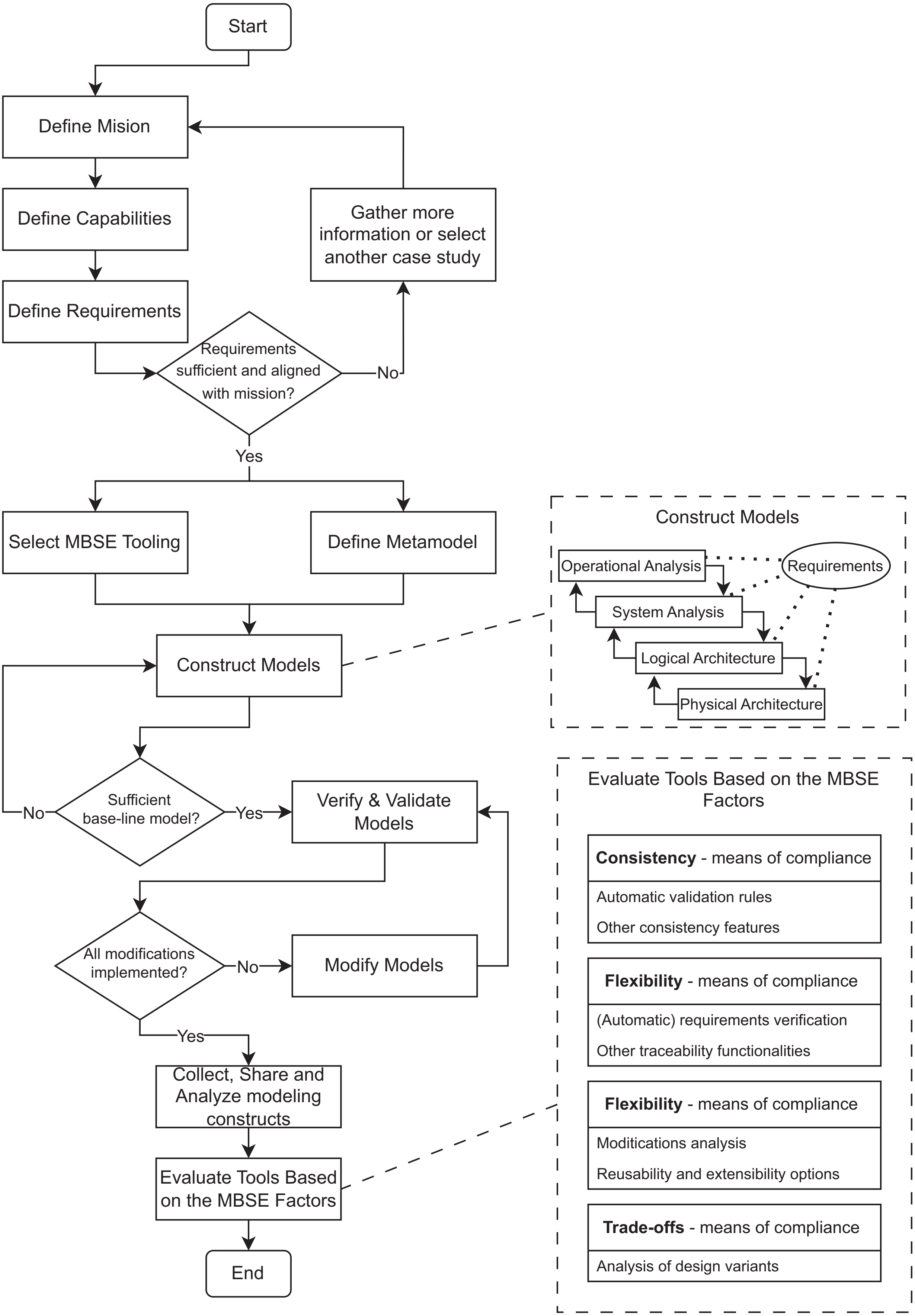

Start
Define Mision
Define Capabilities
Define Requirements
Gather more information or select another case study
Requirements sufficient and aligned with mission?
No
Yes
Select MBSE Tooling
Define Metamodel
Construct Models
Sufficient base-line model?
No
Yes
Verify & Validate Models
All modifications implemented?
No
Modify Models
Yes
Collect, Share and Analyze modeling constructs
Evaluate Tools Based on the MBSE Factors
End
Construct Models
Operational Analysis
Requirements
System Analysis
Logical Architecture
Physical Architecture
Evaluate Tools Based on the MBSE Factors
Consistency - means of compliance
Automatic validation rules
Other consistency features
Flexibility - means of compliance
(Automatic) requirements verification
Other traceability functionalities
Flexibility - means of compliance
Moditications analysis
Reusability and extensibility options
Trade-offs - means of compliance
Analysis of design variants

FIGURE 1 | Flowchart of the proposed research process.

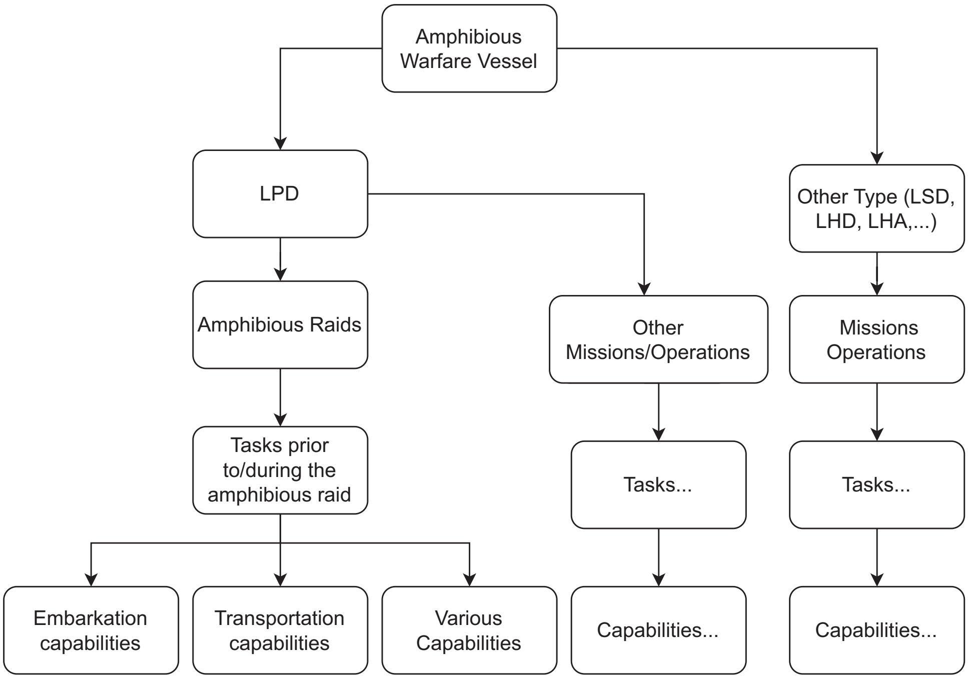

Amphibious Warfare Vessel
LPD
Other Type (LSD, LHD, LHA,...)
Amphibious Raids
Other Missions/Operations
Missions Operations
Tasks prior to/during the amphibious raid
Tasks...
Tasks...
Embarkation capabilities
Transportation capabilities
Various Capabilities
Capabilities...
Capabilities...

FIGURE 2 | Mapping LPD vessel's capabilities to the amphibious raid mission.

of the amphibious raid. The example mission consists of two phases:

- **Pre-Raid Phase**: Initiates with the embarkation of personnel and equipment onto the LPD from the base. It emphasizes loading and readiness procedures essential for mission commencement.
- **Assault Phase**: Encompasses the execution of the amphibious raid until its completion. This phase includes:
  1. *Ship-to-Shore Movement*: using amphibious landing crafts, aircraft, and other assets to deploy the AF and equipment from the LPD to designated landing zones.
  2. *Engagement Stage*: Involves operational actions by the AF to secure objectives, with the LPD providing crucial support through logistical, surveillance, rescue, and other essential capabilities
  3. *Withdrawal Stage*: Concludes with the extraction of forces and equipment from the landing zones back to the LPD, preparing for return to base.

This simplified framework aims to enhance comprehension of the ship's operational objectives within each of these distinct phases. The phase involving the ship's return to base has been omitted, as it closely resembles the initial stage and offers minimal additional value.

Step 2: Defining Capabilities defines the mission for the LPD vessel. Although the case study focuses on a single major amphibious mission area, it can be scaled up to encompass other missions or broader warship designs as part of further research. In a practical LPD design project, all potential missions undergo rigorous evaluation and modeling, with initial models evolving into progressively detailed versions over time. By focusing on a specific mission for the LPD vessel, this method provides insights into the essential capabilities needed to achieve mission objectives. Figure 2 illustrates how capabilities are aligned with the example mission.

In **Step 3: Define Requirements**, the requirements are based on a simplified set derived from mission-specific needs and similar vessel criteria, serving as foundational principles for modeling within MBSE tools and enabling a comparative assessment. While a comprehensive justification of these fictitious requirements is beyond the study's scope, their formulation aims to streamline essential subsystems and components, ensuring a clear focus on operational objectives across different mission phases. The requirements are primarily functional, specifying general capabilities that necessitate particular technological equipment. Potential ambiguities and conflicts are intentionally included to also record the tools' effectiveness in managing such complexities. Each requirement is identified by a unique code reflecting its derivation procedure, which facilitates clarity and traceability. The compiled requirements are detailed in Table A.1.

Step 4: Select MBSE Tooling defines the rationale for MBSE tooling selection. The authors have conducted a review of commonly used combinations of MBSE methods, tools, and languages. The review discusses the strengths and weaknesses of these combinations according to existing literature. Among those are CDP4-COMET (tool) [47] and Capella (tool) [48], as well as SysML tools like CORE [49], Cameo EA [50], Rhapsody [51], and so forth. The findings of this comparison are consolidated and presented in Table 2.

Based on these findings, the first tool selected is Capella. The predefined Arcadia methodology in the Capella MBSE tool aligns well with the author's definition of systems architecture, making it a suitable choice. Its visualization, simplicity, and user-friendliness contribute to its suitability, along with the guidance

TABLE 2 | Comparison of MBSE tools-methods-languages.

Tool	Method	Language	Advantages	Limitations
Capella	Arcadia	Domain-specific language	Flexibility Functional modeling excellence Simplicity and beginner-friendliness Open source Visualization	Predefined methodology Version-saving Layer skippability Commercial add-ons
CDP4-COMET	Concurrent design	ECSS-E-TM-10-25	Multidisciplinary and collaboration Comparison of alternatives Reusability Easy to learn Open source	Absence of diagrams Limited maritime adoption Requires larger monitors
CORE Cameo EA Rhapsody	Vitech MBSE methodology OOSEM IBM Harmony for SE	SysML	Visualization Tool and methodology independent Traceability management SysML V2	Ambiguous concept of function Functional analysis Not meant for beginners Expensive commercial license

it offers to inexperienced users. The second tool selected for this project is the CDP4-COMET. The study [52] was conducted in collaboration with Starion, the company responsible for the development of this MBSE tool. The decision to use CDP4-COMET is supported by direct access to experts with extensive knowledge in using and developing the tool. Furthermore, participation in ship design projects involving CDP4-COMET highlights its applicability in the maritime industry, where its use is less common, and helps address challenges such as the limited availability of ship-specific templates. The tool's ease of learning is also significant. Its advantages in reusability and the comparison of alternatives are relevant to validating the anticipated benefits of consistency and trade-offs. CDP4-COMET supports MBSE through the concurrent design (CD) method, enabling a more integrated design process where trade-offs are evaluated by the customer, and design challenges are addressed in a multidisciplinary context. This approach is well-suited to the complexities of ship design, making CDP4-COMET an appropriate choice for this project.

Step 5: Define Metamodel establishes a common understanding of design challenges in complex systems development, guiding subsequent modeling activities and decision-making. The system architecture development for the LPD vessel spans across multiple levels as depicted in the metamodel shown in Figure 3:

- **Operational Analysis**: Identifies future users and their objectives, resulting in operational entities (actors) and their activities, represented in orange
- **System Analysis**: Defines system functions derived from operational activities, modeling interactions as system functional exchanges, represented in green
- **Logical Architecture**: Decomposes system functions into logical functions and assigns them to subsystems, ensuring alignment with requirements, represented in blue
- **Physical Architecture**: Refines logical functions into physical functions and breaks down subsystems to the equipment level, validating adherence to requirements, represented in yellow

Requirements are incorporated into the models, characterized by descriptions and IDs, and mapped to the appropriate level using "satisfy" relationships. Parameters such as Ship Work Breakdown System (SWBS) coding, mass, center of gravity, and electric load may be assigned to modeling elements.

4.2 | Modeling Effort

Once the metamodel is defined, the modeling effort progresses into **Step 6: Constructing MBSE Models**, explained in detail in the following subsections.

4.2.1 | Modeling in Capella

Capella is a system architecture modeling tool based on the Arcadia methodology. As such, it supports the definition of needs and solutions through a multi-layered structured analysis. Visualization of the operational, as well as the functional (and non-functional), analysis offers detailed insights into the needs and objectives related to a system. Moreover, views on the logical and physical layers present potential solutions through architectural design. The vast majority of the views in this tool are provided in the form of architecture diagrams, breakdown diagrams, and exchange scenarios. In this project, Capella version 6.1 was used. To enhance its capabilities, open-source add-ons such as "Requirements Viewpoint" and "XHTML Documentation Generation," along with sample add-ons like "Basic Mass Viewpoint," were installed and used during the architecture development.

The fundamental components of this conceptual model are the architecture blank diagrams for each layer: operational (OAB) in Figure 4, system (SAB) in Figure 5, logical (LAB) in Figure 6, and physical (PAB). Despite their structural similarity, each has a different purpose and level of detail. Additionally, the secondary diagrams mentioned during the modeling effort also constitute

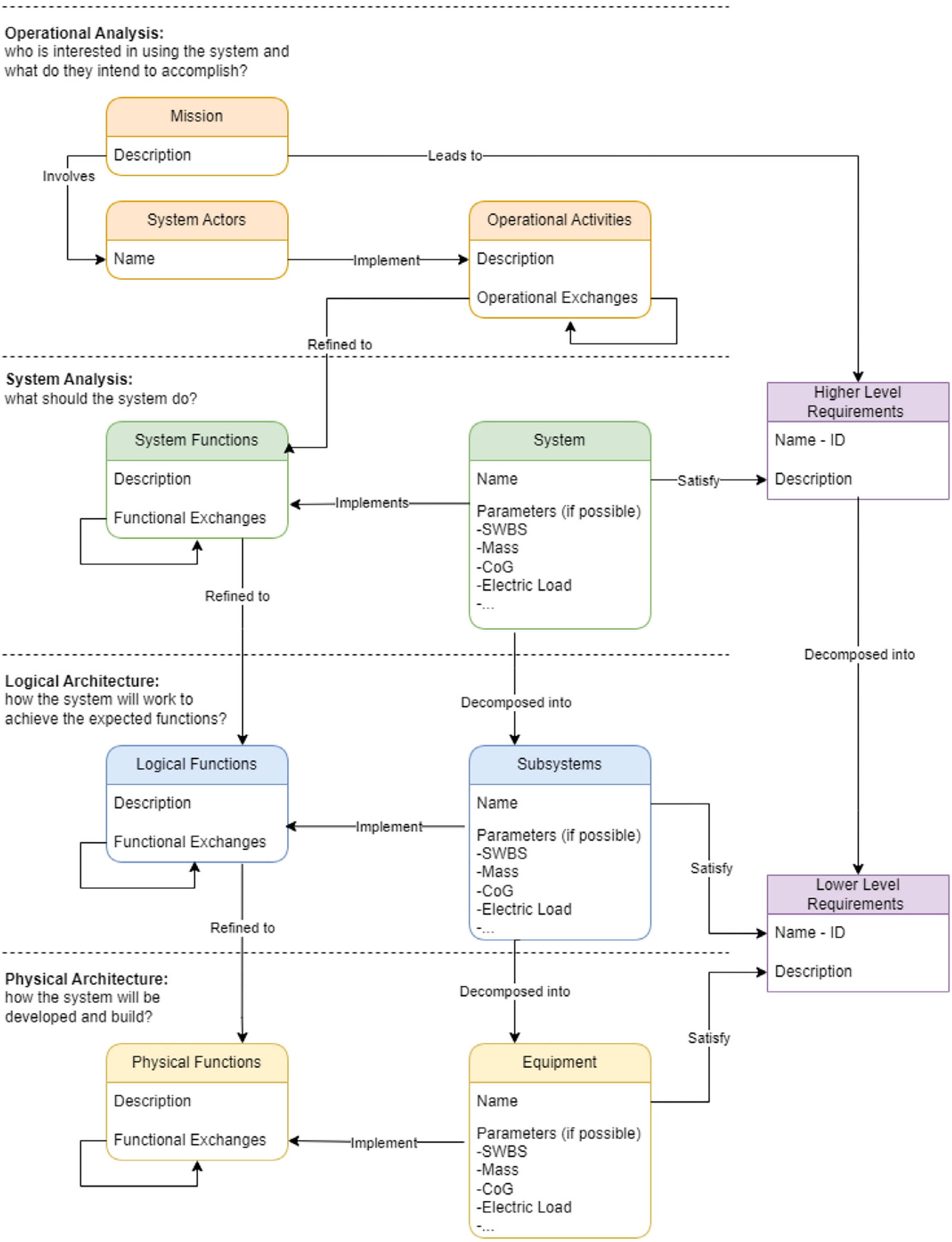


FIGURE 3 | Metamodel of the systems architecture.

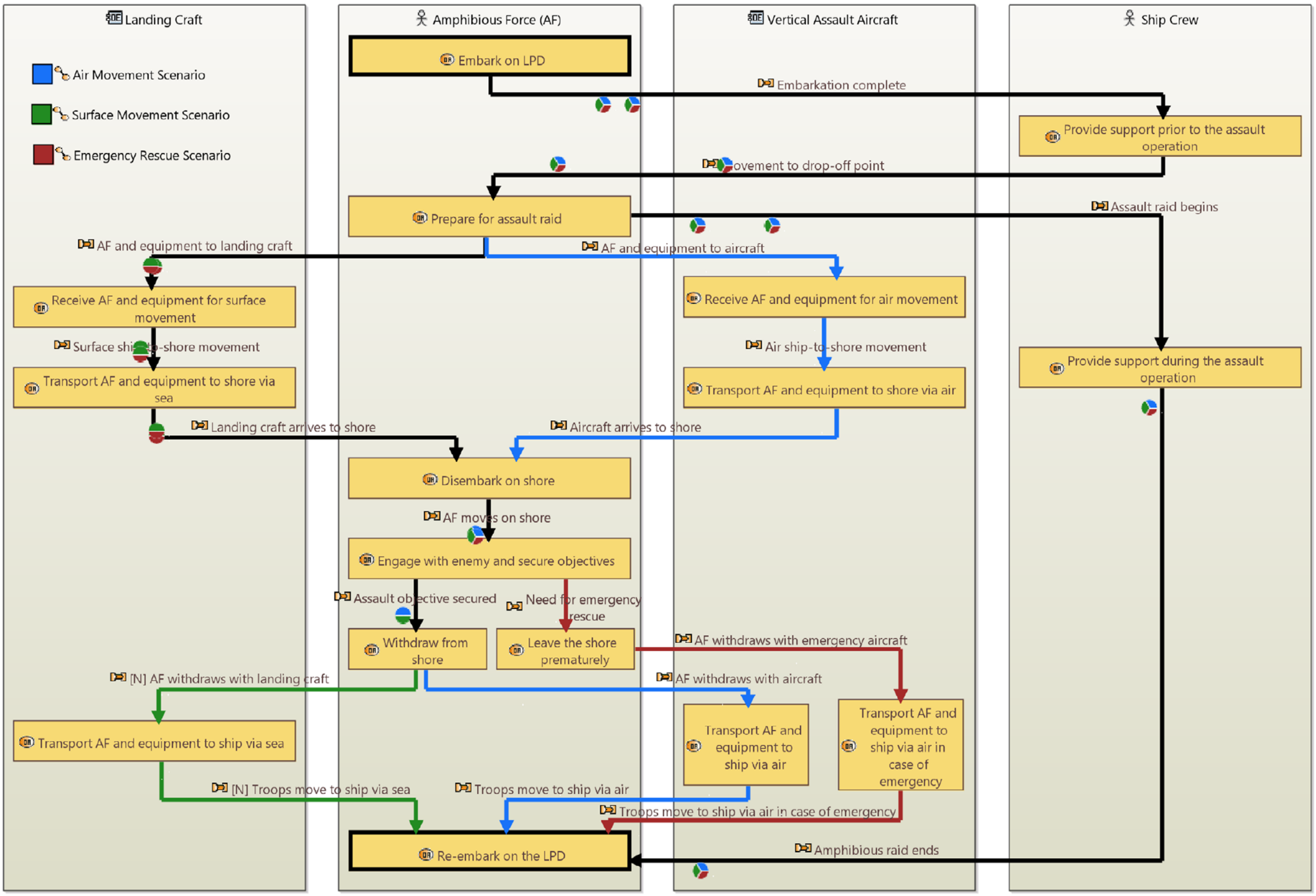

Landing Craft
Amphibious Force (AF)
Vertical Assault Aircraft
Ship Crew
🟦 Air Movement Scenario
🟩 Surface Movement Scenario
🟥 Emergency Rescue Scenario
Embark on LPD
Embarkation complete
Provide support prior to the assault operation
Movement to drop-off point
Prepare for assault raid
Assault raid begins
AF and equipment to landing craft
AF and equipment to aircraft
Receive AF and equipment for surface movement
Receive AF and equipment for air movement
Surface ship-to-shore movement
Air ship-to-shore movement
Provide support during the assault operation
Transport AF and equipment to shore via sea
Transport AF and equipment to shore via air
Landing craft arrives to shore
Aircraft arrives to shore
Disembark on shore
AF moves on shore
Engage with enemy and secure objectives
Assault objective secured
Need for emergency rescue
Withdraw from shore
Leave the shore prematurely
AF withdraws with emergency aircraft
[N] AF withdraws with landing craft
AF withdraws with aircraft
Transport AF and equipment to ship via sea
Transport AF and equipment to ship via air
Transport AF and equipment to ship via air in case of emergency
[N] Troops move to ship via sea
Troops move to ship via air
Troops move to ship via air in case of emergency
Amphibious raid ends
Re-embark on the LPD

FIGURE 4 | Operational architecture blank diagram (OAB) of the LPD model in Capella.

significant modeling constructs, crucial for the completeness of this conceptual model. What enhances the utility of all these diagrams is their interconnectedness, which ensures consistency across various perspectives.

Figure 7 presents a comprehensive view of the physical architecture, continuing the modeling logic used in the creation of OAB, SAB, and LAB diagrams. The diagram features a central white rectangle representing the vessel, surrounded by smaller light blue rectangles denoting the four main actors executing functions highlighted in green. Within the system, yellow boxes represent subsystems, illustrating containment relationships. Each subsystem contains blue boxes representing pieces of equipment. These boxes house physical functions depicted in green. Functional exchanges, component exchanges, and physical exchanges were intentionally omitted for clarity in analysis. Requirements are visualized using the "Requirements Viewpoint" add-on. Higher-level requirements are marked in pink, while lower-level requirements are in gray and white, with white denoting more refined requirements. Arrows denote traces both among requirements and between requirements and specific technological solutions.

Verification of the Capella model involves confirming the vessel model's alignment with specified requirements from Table A.1 through manual creation and linkage of requirements. Qualitative requirements that directly link to specific equipment can be visually verified, but those involving dimensions or arithmetic comparisons pose challenges due to the tool's limitations with parametric data, making it less user-friendly for such detailed analysis. In the validation phase, Capella's built-in validation rules ensure adherence to language constructs and identify errors categorized into several categories. Resolving detected errors is prioritized to advance to the next architectural level, while warnings indicate areas for improvement. Once the baseline model is established, the focus shifts to assessing the MBSE environment's flexibility in accommodating evolving requirements and facilitating design modifications. The initial focus is on consumer set modifications, involving additions and removals of equipment. For instance, adding a piece of new equipment like an anchor entails introducing a new system function at the system analysis layer, transitioning through logical and physical layers with automated updates to associated diagrams and streamlined function allocation. Conversely, removing equipment is facilitated by the tool's automation and guided processes, making the task straightforward. Each modification necessitates revisiting **Step 7 for model Validation and Verification** to ensure compliance with modeling standards, project requirements, and the designated design strategy.

4.2.2 | Modeling in CDP4-COMET

CDP4-COMET supports MBSE using the CD method and is, thus, a collaborative MBSE tool in which all key stakeholders have

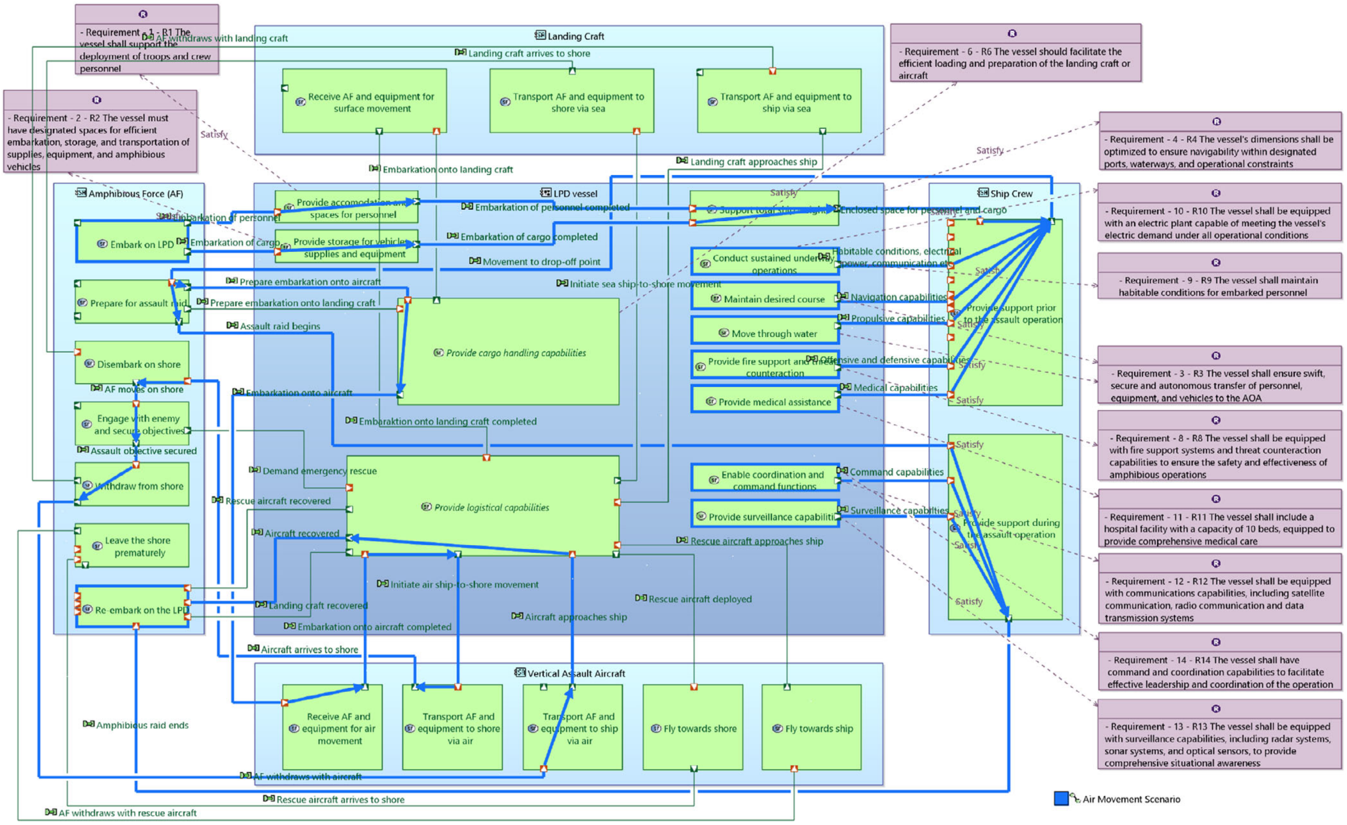

- Requirement - 1 - R1 The vessel shall support the deployment of troops and crew personnel
- Requirement - 2 - R2 The vessel must have designated spaces for efficient embarkation, storage, and transportation of supplies, equipment, and amphibious vehicles
- Requirement - 6 - R6 The vessel should facilitate the efficient loading and preparation of the landing craft or aircraft
- Requirement - 4 - R4 The vessel's dimensions shall be optimized to ensure navigability within designated ports, waterways, and operational constraints
- Requirement - 10 - R10 The vessel shall be equipped with an electric plant capable of meeting the vessel's electric demand under all operational conditions
- Requirement - 9 - R9 The vessel shall maintain habitable conditions for embarked personnel
- Requirement - 3 - R3 The vessel shall ensure swift, secure and autonomous transfer of personnel, equipment, and vehicles to the AOA
- Requirement - 8 - R8 The vessel shall be equipped with fire support systems and threat counteraction capabilities to ensure the safety and effectiveness of amphibious operations
- Requirement - 11 - R11 The vessel shall include a hospital facility with a capacity of 10 beds, equipped to provide comprehensive medical care
- Requirement - 12 - R12 The vessel shall be equipped with communications capabilities, including satellite communication, radio communication and data transmission systems
- Requirement - 14 - R14 The vessel shall have command and coordination capabilities to facilitate effective leadership and coordination of the operation
- Requirement - 13 - R13 The vessel shall be equipped with surveillance capabilities, including radar systems, sonar systems, and optical sensors, to provide comprehensive situational awareness
Satisfy
Landing Craft
Landing craft arrives to shore
AF withdraws with landing craft
Receive AF and equipment for surface movement
Transport AF and equipment to shore via sea
Transport AF and equipment to ship via sea
Embarkation onto landing craft
Landing craft approaches ship
Amphibious Force (AF)
Embark on LPD
Prepare for assault raid
Disembark on shore
AF moves on shore
Engage with enemy and secure objectives
Assault objective secured
Withdraw from shore
Leave the shore prematurely
Re-embark on the LPD
LPD vessel
Provide accommodation spaces for personnel
Provide storage for vehicles, supplies and equipment
Embarkation of personnel
Embarkation of cargo
Embarkation of personnel completed
Embarkation of cargo completed
Movement to drop-off point
Prepare embarkation onto aircraft
Prepare embarkation onto landing craft
Initiate sea ship-to-shore movement
Assault raid begins
Provide cargo handling capabilities
Embarkation onto aircraft
Embarkation onto landing craft completed
Demand emergency rescue
Rescue aircraft recovered
Aircraft recovered
Provide logistical capabilities
Initiate air ship-to-shore movement
Landing craft recovered
Embarkation onto aircraft completed
Rescue aircraft deployed
Aircraft approaches ship
Rescue aircraft approaches ship
Support to all ship systems
Conduct sustained underway operations
Maintain desired course
Move through water
Provide fire support and threat counteraction
Provide medical assistance
Enable coordination and command functions
Provide surveillance capabilities
Enclosed space for personnel and cargo
Habitable conditions, electrical power, communication etc.
Navigation capabilities
Propulsive capabilities
Offensive and defensive capabilities
Medical capabilities
Command capabilities
Surveillance capabilities
Ship Crew
Provide support prior to the assault operation
Provide support during the assault operation
Aircraft arrives to shore
Vertical Assault Aircraft
Receive AF and equipment for air movement
Transport AF and equipment to shore via air
Transport AF and equipment to ship via air
Fly towards shore
Fly towards ship
Amphibious raid ends
AF withdraws with aircraft
Rescue aircraft arrives to shore
AF withdraws with rescue aircraft
Air Movement Scenario

FIGURE 5 | System architecture blank diagram (SAB) of the LPD model in Capella.

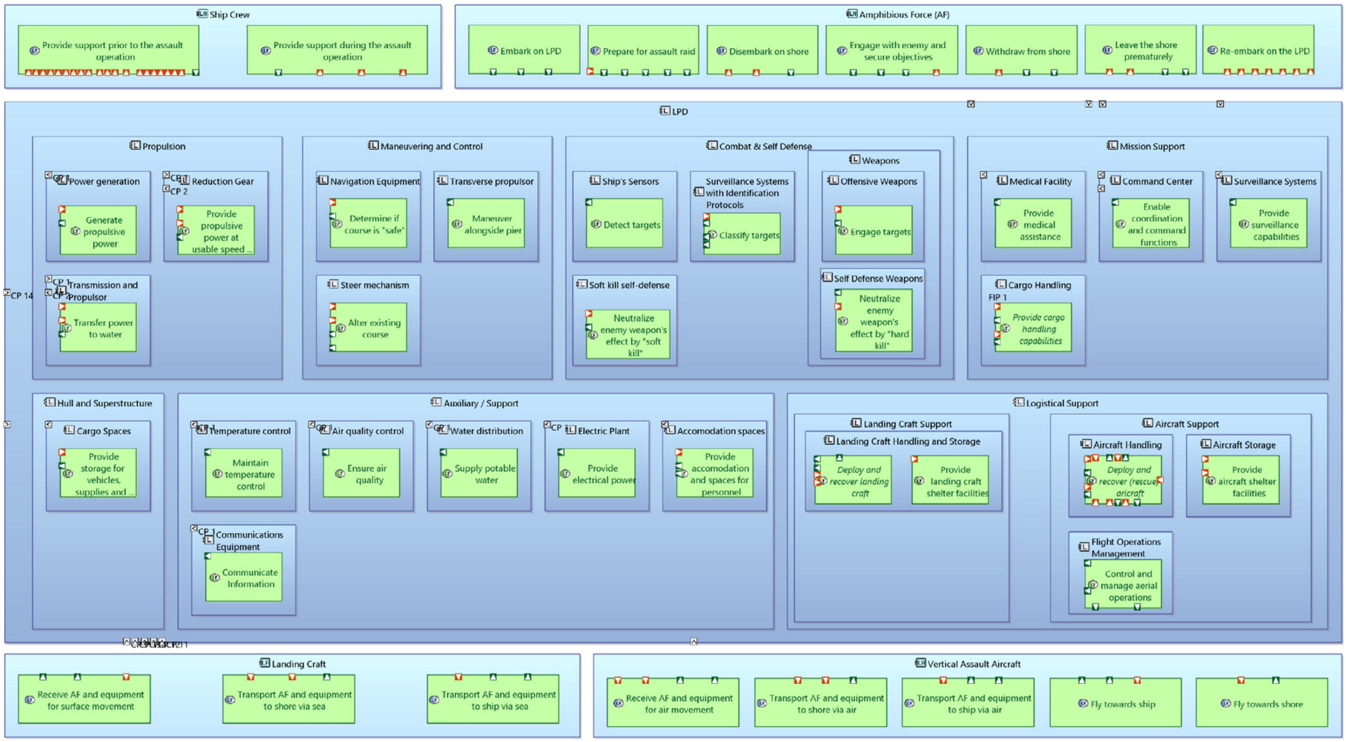

Ship Crew
Provide support prior to the assault operation
Provide support during the assault operation
Amphibious Force (AF)
Embark on LPD
Prepare for assault raid
Disembark on shore
Engage with enemy and secure objectives
Withdraw from shore
Leave the shore prematurely
Re-embark on the LPD
LPD
Propulsion
Power generation
Generate propulsive power
Reduction Gear
Provide propulsive power at usable speed
Transmission and Propulsor
Transfer power to water
Maneuvering and Control
Navigation Equipment
Determine if course is "safe"
Transverse propulsor
Maneuver alongside pier
Steer mechanism
Alter existing course
Combat & Self Defense
Ship's Sensors
Detect targets
Surveillance Systems with Identification Protocols
Classify targets
Weapons
Offensive Weapons
Engage targets
Soft kill self-defense
Neutralize enemy weapon's effect by "soft kill"
Self Defense Weapons
Neutralize enemy weapon's effect by "hard kill"
Mission Support
Medical Facility
Provide medical assistance
Command Center
Enable coordination and command functions
Surveillance Systems
Provide surveillance capabilities
Cargo Handling
Provide cargo handling capabilities
Hull and Superstructure
Cargo Spaces
Provide storage for vehicles, supplies and ...
Auxiliary / Support
Temperature control
Maintain temperature control
Air quality control
Ensure air quality
Water distribution
Supply potable water
Electric Plant
Provide electrical power
Accomodation spaces
Provide accomodation and spaces for personnel
Communications Equipment
Communicate Information
Logistical Support
Landing Craft Support
Landing Craft Handling and Storage
Deploy and recover landing craft
Provide landing craft shelter facilities
Aircraft Support
Aircraft Handling
Deploy and recover (rescue) aircraft
Aircraft Storage
Provide aircraft shelter facilities
Flight Operations Management
Control and manage aerial operations
Landing Craft
Receive AF and equipment for surface movement
Transport AF and equipment to shore via sea
Transport AF and equipment to ship via sea
Vertical Assault Aircraft
Receive AF and equipment for air movement
Transport AF and equipment to shore via air
Transport AF and equipment to ship via air
Fly towards ship
Fly towards shore

FIGURE 6 | Logical architecture blank diagram (LAB) of the LPD model in Capella.

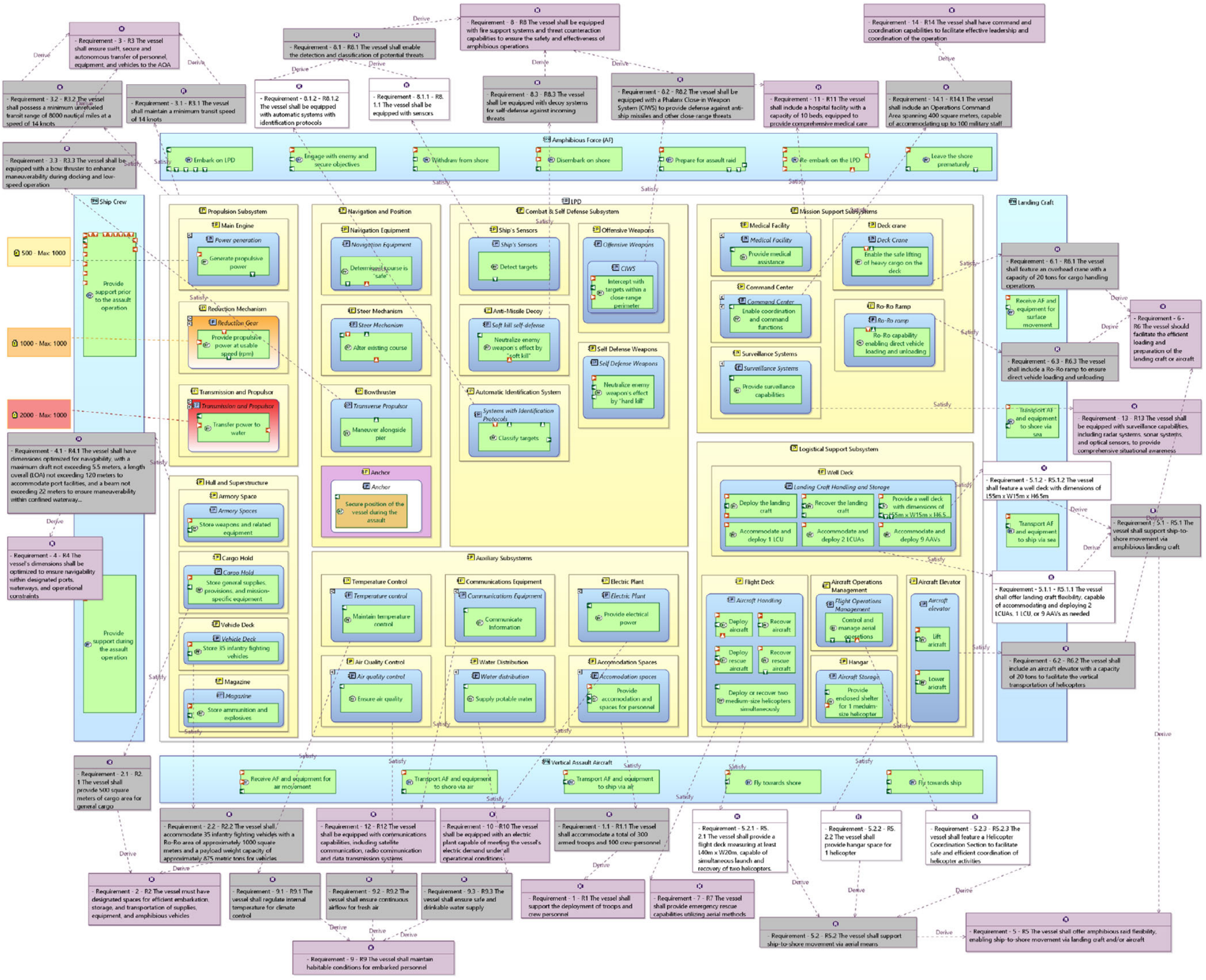
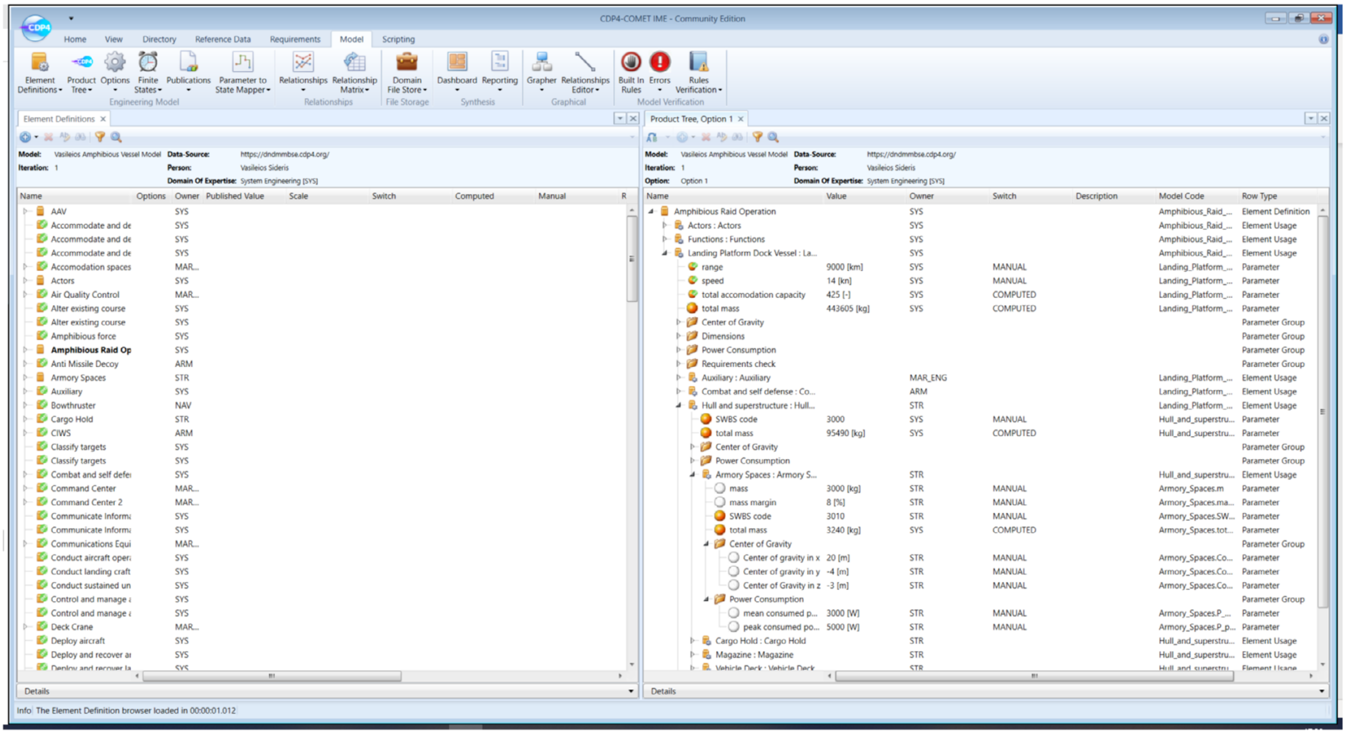

- Requirement - 3 - R3 The vessel shall ensure swift, secure and autonomous transfer of personnel, equipment, and vehicles to the AOA
- Requirement - 8.1 - R8.1 The vessel shall enable the detection and classification of potential threats
- Requirement - 8 - R8 The vessel shall be equipped with fire support systems and threat counteraction capabilities to ensure the safety and effectiveness of amphibious operations
- Requirement - 14 - R14 The vessel shall have command and coordination capabilities to facilitate effective leadership and coordination of the operation
- Requirement - 3.2 - R3.2 The vessel shall possess a minimum unrefueled transit range of 8000 nautical miles at a speed of 14 knots
- Requirement - 3.1 - R3.1 The vessel shall maintain a minimum transit speed of 14 knots
- Requirement - 8.1.2 - R8.1.2 The vessel shall be equipped with automatic systems with identification protocols
- Requirement - 8.1.1 - R8.1.1 The vessel shall be equipped with sensors
- Requirement - 8.3 - R8.3 The vessel shall be equipped with decoy systems for self-defense against incoming threats
- Requirement - 8.2 - R8.2 The vessel shall be equipped with a Phalanx Close-in Weapon System (CIWS) to provide defense against anti-ship missiles and other close-range threats
- Requirement - 11 - R11 The vessel shall include a hospital facility with a capacity of 10 beds, equipped to provide comprehensive medical care
- Requirement - 14.1 - R14.1 The vessel shall include an Operations Command Area spanning 400 square meters, capable of accommodating up to 100 military staff
- Requirement - 3.3 - R3.3 The vessel shall be equipped with a bow thruster to enhance maneuverability during docking and low-speed operation
Derive
Satisfy
Amphibious Force (AF)
Embark on LPD
Engage with enemy and secure objectives
Withdraw from shore
Disembark on shore
Prepare for assault raid
Re-embark on the LPD
Leave the shore prematurely
Ship Crew
Provide support prior to the assault operation
Provide support during the assault operation
500 - Max 1000
1000 - Max 1000
2000 - Max 1000
LPD
Propulsion Subsystem
Main Engine
Power generation
Generate propulsive power
Reduction Mechanism
Reduction Gear
Provide propulsive power at usable speed (rpm)
Transmission and Propulsor
Transmission and Propulsor
Transfer power to water
Navigation and Position
Navigation Equipment
Navigation Equipment
Determine if course is "safe"
Steer Mechanism
Steer Mechanism
Alter existing course
Bowthruster
Transverse Propulsor
Maneuver alongside pier
Anchor
Anchor
Secure position of the vessel during the assault
Combat & Self Defense Subsystem
Ship's Sensors
Ship's Sensors
Detect targets
Anti-Missile Decoy
Soft kill self-defense
Neutralize enemy weapon's effect by "soft kill"
Automatic Identification System
Systems with Identification Protocols
Classify targets
Offensive Weapons
Offensive Weapons
CIWS
Intercept with targets within a close-range perimeter
Self Defense Weapons
Self Defense Weapons
Neutralize enemy weapon's effect by "hard kill"
Mission Support Subsystems
Medical Facility
Medical Facility
Provide medical assistance
Command Center
Command Center
Enable coordination and command functions
Surveillance Systems
Surveillance Systems
Provide surveillance capabilities
Deck crane
Deck Crane
Enable the safe lifting of heavy cargo on the deck
Ro-Ro Ramp
Ro-Ro ramp
Ro-Ro capability enabling direct vehicle loading and unloading
Hull and Superstructure
Armory Space
Armory Spaces
Store weapons and related equipment
Cargo Hold
Cargo Hold
Store general supplies, provisions, and mission-specific equipment
Vehicle Deck
Vehicle Deck
Store 35 infantry fighting vehicles
Magazine
Magazine
Store ammunition and explosives
Auxiliary Subsystems
Temperature Control
Temperature control
Maintain temperature control
Communications Equipment
Communications Equipment
Communicate Information
Electric Plant
Electric Plant
Provide electrical power
Air Quality Control
Air quality control
Ensure air quality
Water Distribution
Water distribution
Supply potable water
Accomodation Spaces
Accomodation spaces
Provide accomodation and spaces for personnel
Logistical Support Subsystem
Well Deck
Landing Craft Handling and Storage
Deploy the landing craft
Recover the landing craft
Provide a well deck with dimensions of L55m x W15m x H6.5
Accommodate and deploy 1 LCU
Accommodate and deploy 2 LCUAs
Accommodate and deploy 9 AAVs
Flight Deck
Aircraft Handling
Deploy aircraft
Recover aircraft
Deploy rescue aircraft
Recover rescue aircraft
Deploy or recover two medium-size helicopters simultaneously
Aircraft Operations Management
Flight Operations Management
Control and manage aerial operations
Hangar
Aircraft Storage
Provide enclosed shelter for 1 meduim-size helicopter
Aircraft Elevator
Aircraft elevator
Lift aricraft
Lower aricraft
Landing Craft
Receive AF and equipment for surface movement
Transport AF and equipment to shore via sea
Transport AF and equipment to ship via sea
- Requirement - 6.1 - R6.1 The vessel shall feature an overhead crane with a capacity of 20 tons for cargo handling operations
- Requirement - 6 - R6 The vessel should facilitate the efficient loading and preparation of the landing craft or aircraft
- Requirement - 6.3 - R6.3 The vessel shall include a Ro-Ro ramp to ensure direct vehicle loading and unloading
- Requirement - 13 - R13 The vessel shall be equipped with surveillance capabilities, including radar systems, sonar systems, and optical sensors, to provide comprehensive situational awareness
- Requirement - 5.1.2 - R5.1.2 The vessel shall feature a well deck with dimensions of L55m x W15m x H6.5m
- Requirement - 5.1 - R5.1 The vessel shall support ship-to-shore movement via amphibious landing craft
- Requirement - 5.1.1 - R5.1.1 The vessel shall offer landing craft flexibility, capable of accommodating and deploying 2 LCUAs, 1 LCU, or 9 AAVs as needed
- Requirement - 6.2 - R6.2 The vessel shall include an aircraft elevator with a capacity of 20 tons to facilitate the vertical transportation of helicopters
- Requirement - 4.1 - R4.1 The vessel shall have dimensions optimized for navigability, with a maximum draft not exceeding 5.5 meters, a length overall (LOA) not exceeding 120 meters to accommodate port facilities, and a beam not exceeding 22 meters to ensure maneuverability within confined waterway...
- Requirement - 4 - R4 The vessel's dimensions shall be optimized to ensure navigability within designated ports, waterways, and operational constraints
Vertical Assault Aircraft
Receive AF and equipment for air movement
Transport AF and equipment to shore via air
Transport AF and equipment to ship via air
Fly towards shore
Fly towards ship
- Requirement - 2.1 - R2.1 The vessel shall provide 500 square meters of cargo area for general cargo
- Requirement - 2.2 - R2.2 The vessel shall accommodate 35 infantry fighting vehicles with a Ro-Ro area of approximately 1000 square meters and a payload weight capacity of approximately 875 metric tons for vehicles
- Requirement - 12 - R12 The vessel shall be equipped with communications capabilities, including satellite communication, radio communication and data transmission systems
- Requirement - 10 - R10 The vessel shall be equipped with an electric plant capable of meeting the vessel's electric demand under all operational conditions
- Requirement - 1.1 - R1.1 The vessel shall accommodate a total of 300 armed troops and 100 crew-personnel
- Requirement - 5.2.1 - R5.2.1 The vessel shall provide a flight deck measuring at least L40m x W20m, capable of simultaneous launch and recovery of two helicopters.
- Requirement - 5.2.2 - R5.2.2 The vessel shall provide hangar space for 1 helicopter
- Requirement - 5.2.3 - R5.2.3 The vessel shall feature a Helicopter Coordination Section to facilitate safe and efficient coordination of helicopter activities
- Requirement - 2 - R2 The vessel must have designated spaces for efficient embarkation, storage, and transportation of supplies, equipment, and amphibious vehicles
- Requirement - 9.1 - R9.1 The vessel shall regulate internal temperature for climate control
- Requirement - 9.2 - R9.2 The vessel shall ensure continuous airflow for fresh air
- Requirement - 9.3 - R9.3 The vessel shall ensure safe and drinkable water supply
- Requirement - 1 - R1 The vessel shall support the deployment of troops and crew personnel
- Requirement - 7 - R7 The vessel shall provide emergency rescue capabilities utilizing aerial methods
- Requirement - 5.2 - R5.2 The vessel shall support ship-to-shore movement via aerial means
- Requirement - 5 - R5 The vessel shall offer amphibious raid flexibility, enabling ship-to-shore movement via landing craft and/or aircraft
- Requirement - 9 - R9 The vessel shall maintain habitable conditions for embarked personnel

FIGURE 7 | Physical architecture blank diagram (PAB) of the LPD model in Capella.

access to the model as well as ownership of the information, depending on their domain of expertise. In this model, a system decomposition is established in which elements of the system and associated parameters represent factors that enable analysis of the key challenges in an ESSD problem. This project used the CDP4-COMET IME (Integrated Modelling Environment—Desktop Application) version 9.5.0.0.

In CDP4-COMET, the system is divided into domains of expertise, with each team member responsible for specific aspects of the design, ensuring data quality and minimizing errors. Ownership is managed through role-based access control, with examples like armament, marine engineering, and naval architecture in the LPD model. Despite the authors handling all domains for demonstration purposes, this setup highlights CDP4-COMET's ability to distribute responsibilities and provide appropriate stakeholder access. An element definition represents entities such as systems, subsystems, equipment, or functions owned by a domain of expertise. Element usage denotes the inclusion of an element definition within another, enabling the creation of complex architectures from simpler building blocks. The elements are listed in the element definition browser, with the architecture shown in the product tree.

Similar to the modeling in Capella, the model in CDP4-COMET adhered to the modeling logic prescribed by the metamodel. To recreate the model in CDP4-COMET, the amphibious raid operation was categorized as the "mission" at the top level, with nested elements for actors, functions, and the Landing Platform Dock Vessel. Each actor, such as the Amphibious Force and Ship Crew, was categorized as "actors," while functions spanned four architectural layers: operational analysis, system analysis, logical architecture, and physical architecture. In system analysis, operational activities were mapped to system functions using a "derive" relationship, visualized in a relationship matrix. The latter allowed for the visualization of the modeling elements and their relationships. Logical architecture involved transitioning system functions to new logical functions and defining subsystems, visualized with "implement" relationships. Finally, in the Physical Architecture layer, logical functions were refined into physical functions and linked to equipment using "implement" relationships. Figure 8 provides a snapshot of a segment of



Model: Vasileios Amphibious Vessel Model **Data-Source:** https://dndmmbse.cdp4.org/
Iteration: 1 **Person:** Vasileios Sideris
Domain Of Expertise: System Engineering [SYS]

Name	Options	Owner	Published Value	Scale	Switch	Computed	Manual	R
AAV		SYS						
Accommodate and de		SYS						
Accommodate and de		SYS						
Accommodate and de		SYS						
Accomodation spaces		MAR...						
Actors		SYS						
Air Quality Control		MAR...						
Alter existing course		SYS						
Alter existing course		SYS						
Amphibious force		SYS						
Amphibious Raid Op		SYS						
Anti Missile Decoy		ARM						
Armory Spaces		STR						
Auxiliary		SYS						
Bowthruster		NAV						
Cargo Hold		STR						
CIWS		ARM						
Classify targets		SYS						
Classify targets		SYS						
Combat and self defe		SYS						
Command Center		MAR...						
Command Center 2		MAR...						
Communicate Informa		SYS						
Communicate Informa		SYS						
Communications Equi		MAR...						
Conduct aircraft opera		SYS						
Conduct landing craft		SYS						
Conduct sustained un		SYS						
Control and manage a		SYS						
Control and manage a		SYS						
Deck Crane		MAR...						
Deploy aircraft		SYS						
Deploy and recover ai		SYS						
Deploy and recover la		SYS						

Info The Element Definition browser loaded in 00:00:01.012

Model: Vasileios Amphibious Vessel Model **Data-Source:** https://dndmmbse.cdp4.org/
Iteration: 1 **Person:** Vasileios Sideris
Option: Option 1 **Domain Of Expertise:** System Engineering [SYS]

Name	Value	Owner	Switch	Description	Model Code	Row Type
Amphibious Raid Operation		SYS			Amphibious_Raid_...	Element Definition
Actors : Actors		SYS			Amphibious_Raid_...	Element Usage
Functions : Functions		SYS			Amphibious_Raid_...	Element Usage
Landing Platform Dock Vessel : La...		SYS			Amphibious_Raid_...	Element Usage
range	9000 [km]	SYS	MANUAL		Landing_Platform_...	Parameter
speed	14 [kn]	SYS	MANUAL		Landing_Platform_...	Parameter
total accomodation capacity	425 [-]	SYS	COMPUTED		Landing_Platform_...	Parameter
total mass	443605 [kg]	SYS	COMPUTED		Landing_Platform_...	Parameter
Center of Gravity						Parameter Group
Dimensions						Parameter Group
Power Consumption						Parameter Group
Requirements check						Parameter Group
Auxiliary : Auxiliary		MAR_ENG			Landing_Platform_...	Element Usage
Combat and self defense : Co...		ARM			Landing_Platform_...	Element Usage
Hull and superstructure : Hull...		STR			Landing_Platform_...	Element Usage
SWBS code	3000	SYS	MANUAL		Hull_and_superstru...	Parameter
total mass	95490 [kg]	SYS	COMPUTED		Hull_and_superstru...	Parameter
Center of Gravity						Parameter Group
Power Consumption						Parameter Group
Armory Spaces : Armory S...		STR			Hull_and_superstru...	Element Usage
mass	3000 [kg]	STR	MANUAL		Armory_Spaces.m	Parameter
mass margin	8 [%]	STR	MANUAL		Armory_Spaces.ma...	Parameter
SWBS code	3010	STR	MANUAL		Armory_Spaces.SW...	Parameter
total mass	3240 [kg]	SYS	COMPUTED		Armory_Spaces.tot...	Parameter
Center of Gravity						Parameter Group
Center of gravity in x	20 [m]	STR	MANUAL		Armory_Spaces.Co...	Parameter
Center of gravity in y	-4 [m]	STR	MANUAL		Armory_Spaces.Co...	Parameter
Center of Gravity in z	-3 [m]	STR	MANUAL		Armory_Spaces.Co...	Parameter
Power Consumption						Parameter Group
mean consumed p...	3000 [W]	STR	MANUAL		Armory_Spaces.P_...	Parameter
peak consumed po...	5000 [W]	STR	MANUAL		Armory_Spaces.P_p...	Parameter
Cargo Hold : Cargo Hold		STR			Hull_and_superstru...	Element Usage
Magazine : Magazine		STR			Hull_and_superstru...	Element Usage
Vehicle Deck : Vehicle Deck		STR			Hull_and_superstru...	Element Usage

FIGURE 8 | Element definition browser (left) and product tree (right) of the LPD model in CDP4-COMET.

the finalized system architecture, displaying detailed element definitions in the browser on the left and the corresponding product tree on the right.

In CDP4-COMET, balances, or budgets, play a crucial role in tracking changes and exploring trade-offs across system requirements, solution architecture, and key parameters like mass, power, costs, and technology readiness. The reporting feature enables users to create custom reports focusing on specific parameters to evaluate overall system performance effectively. Parameters were assigned to the model to demonstrate the utilization of a mass balance report and to verify automatic capabilities effectively.

In the verification and validation step for the CDP4-COMET model of the LPD vessel, each of the 40 requirements was linked to design elements, facilitating automated verification through associated parameters. This process ensured that specific design features met technological criteria, with the use of SWBS coding for equipment inclusion and microsoft Excel for complex arithmetic checks. Validation involved built-in and custom rules to maintain model setup consistency, scrutinizing parameters like mass and center of gravity. Additional checks on mass proportionality, size constraints, and spatial relationships enhanced error detection in the complex system design.

In the **Step 8 - Modify Models** stage of the CDP4-COMET model, adjustments were made to enhance compliance with unmet requirements from the baseline model. The *Options* feature in CDP4-COMET played a pivotal role in enabling these refinements. Consequently, a design alternative was developed with minor variations compared to the baseline, demonstrating the tool's capability to manage and explore different design directions effectively. These modifications underscored the tool's capability to manage alternative design directions within the engineering model efficiently. Consumer set modifications involved adding and adjusting equipment elements, while model modifications showcased the tool's flexibility in incorporating new parameters and updating existing ones to refine the model's fidelity and adaptation to evolving project needs.

4.3 | Assessment of Tools Based on MBSE Factors

This section focuses on the final phase of the proposed process, which centers on validating the benefits of MBSE. The evaluation of each tool encompassed practical demonstrations and tests to gauge their performance. In this paper, the results of this comparative analysis are summarized in Table 3. In the following paragraphs, a review of the factors examined for each tool is presented. Each tool is assessed based on these factors using a five-step scale, ranging from "poor" as the lowest score to "excellent" as the highest, with intermediate evaluations including "fair," "average," and "good," as graded by the authors.

Consistency in Capella:

In summary, Capella supports automatic checks using built-in rules, offering over 300 integrated rules to validate models across different architectural layers. The tool identifies modeling items violating rules and categorizes violations as errors or warnings, providing quick fixes where possible. However, it restricts the creation of new rules, allowing only activation or deactivation of predefined ones. To further enhance consistency, Capella has features like the correct use of modeling elements based on the Arcadia method, automatic view synchronization, and seamless

TABLE 3 | Assessment of Capella and CDP4-COMET in terms of consistency, traceability, flexibility, and trade-offs.

		Capella features			CDP4-COMET features		
Factor	**Means of compliance**	**Positive aspects**	**Negative aspects**	**Overall assessment**	**Positive aspects**	**Negative aspects**	**Overall assessment**
Consistency	Automated checks using built-in/custom validation rules	More than 300 incorporated rules Identification of modeling items violating rules Rule alongside for better understanding Automatic solutions via "Quick Fix" option Severity indication streamlines corrective actions	Customization limited to rule activation/deactivation Automatic transition malfunctions	Good	Custom validation rules allowing tailored checks Detection of violations and error message Possibility for more advanced checks	No severity levels for rules Lack of predefined validation rules Complex error message interpretation	Average
Consistency	Investigation of other consistency functionalities	"Correct" use of modeling elements (Automatic) Transitions between layers Automatic synchronisation of different views	—		Element Definitions and Product Tree views Color-coded parameters and other visuals Copying element definitions (templating technique)	—	
Traceability	Evaluation of requirements verification capabilities	Graphical requirement representation (add-on) Requirement Links Mass Visualization View for editing or viewing	Automatic verification not possible in basic version Visual verification lacks arithmetic comparison capabilities	Average	Automatic verification of requirements Color-coded indicators for visual clarity	Creation of new verification parameters Time-consuming parametric constraint establishment	Good
Traceability	Investigation of other traceability functionalities	Functional chains Semantic Browser Transition functionalities Traceability Matrices	—		Binary relationship rules and Traceability Matrices Monitoring and logging changes	—	

(Continues)

TABLE 3 | (Continued)

		Capella features			CDP4-COMET features		
Factor	**Means of compliance**	**Positive aspects**	**Negative aspects**	**Overall assessment**	**Positive aspects**	**Negative aspects**	**Overall assessment**
Flexibility	Analysis of modification process	Very easy to add/remove/modify elements visually Consistent changes in model and diagram updates Well-guided process and smart shortcuts Impact analysis window before deletion	Adjusting parameters is expected to be challenging	Excellent	Very easy to add elements by drag-and-drop Options feature simplifies modifications	Difficult to analyze the impact of a modification No undo or redo feature included	Good
Flexibility	Evaluation of reusability and extensibility options	No need for new elements; reuse existing ones Transitioned elements easily available for reuse Cloning diagrams reduces workload	—		Cloning technique for modifications Templating technique for creating new elements Reuse of balances for similar models Reuse of existing parameters Reuse of verification and validation rules	—	
Trade-offs	Comparative analysis of design variants	Scenario-based comparison Qualitative analysis by visual inspection	Quantitative analysis is difficult Visual comparison is difficult for complex models	Fair	Custom reports for focused performance evaluation Options for solution direction exploration Reuse reports across multiple projects Instant updates for quick performance overview	Time and coding skills required for new reports	Excellent

transitions between modeling layers. Consequently, it earns an overall rating of "Good", reflecting minor areas for improvement.

Consistency in CDP4-COMET:

CDP4-COMET offers both built-in and customizable rules to sustain internal consistency within the model. It automatically detects violations and issues error messages accordingly. Its standout feature lies in the capability to create custom checks. However, there is room for enhancement, particularly in integrating severity levels into rules and providing clearer guidance for resolving identified errors. Additionally, consistency is maintained through views like element definitions and product tree, which allow users to inspect/modify data and track parameters visually. The templating approach of copying element definitions ensures uniformity throughout the model. Despite these strengths, CDP4-COMET's consistency was evaluated as "Average," indicating some areas for potential improvement.

Traceability in Capella:

In Capella's basic version without extensions, automatic verification of requirements is not possible. However, the requirements viewpoint add-on aids in requirement visualization, allowing for a visual display. Verification in the LPD case relied on linking each requirement to an element with a satisfaction relationship, limited to functional requirements and not covering arithmetic calculations and comparisons. Moreover, other traceability functionalities in the tool include functional chains for illustrating system behavior and the semantic browser for tracing parent/child relationships and enabling quick navigation. Finally, it offers transition functionalities for traceability between architectural layers and traceability matrices for inspecting and creating traces between elements from different levels. Consequently, its overall traceability score is assessed as "Average."

Traceability in CDP4-COMET:

CDP4-COMET stands out for its strong automatic requirements verification, strengthened by the microsoft Excel integration. It efficiently verifies various requirements, from basic functional to intricate quantitative design requirements. Nevertheless, manual creation and direct linking of new parameters solely for verification, together with establishing parametric constraints for each requirement, can be time-consuming and labor-intensive. Next to that, CDP4-COMET enables traceability through defined binary relationships and supports monitoring and logging changes throughout the design, guaranteeing transparent documentation and an overview of model modifications over time. Consequently, it earns an overall rating of "Good."

Flexibility in Capella:

Capella streamlines the visual addition, removal, or modification of elements. It also helps make these changes consistent across the model and provides automatic diagram updates. Nevertheless, modifying parameters is expected to be more challenging and time-consuming, although this aspect has not been extensively investigated, resulting in a neutral assessment. Despite this, the tool offers smart shortcuts and a clear overview of impacted elements, enhancing guidance and flexibility. Moreover, the automatic transition feature encourages reusability by transitioning and reusing elements from previous layers, while the diagram cloning feature significantly reduces workload. Therefore, it earns an overall rating of "Excellent."

Flexibility in CDP4-COMET:

The modeling logic of building blocks and the drag-and-drop technique allow for quick and straightforward modifications in CDP4-COMET. Nonetheless, the lack of an impact analysis view for proposed changes and the absence of undo or redo features complicate error handling and hinder ease in making modifications, particularly in complex projects. On top of that, functionalities like cloning, templating, reusing reports, existing parameters, and verification/validation rules enhance overall flexibility. Consequently, its overall flexibility score is assessed as "Good."

Trade-offs in Capella:

Capella's ability to enhance transparency in trade-offs is hindered by the lack of direct support for quantitative performance parameters without additional extensions. While qualitative trade-off studies are supported through scenarios and visual inspection of diagrams, side-by-side comparisons become challenging with increasing model complexity. Therefore, Capella's inadequacy in comparing design variants is reflected in its assessment, rated as "Fair."

Flexibility in CDP4-COMET:

CDP4-COMET comprises requirements, solution architecture, and key parameters for system performance evaluation. Balances and reporting mechanisms are crucial for tracking changes and studying trade-offs. The tool allows users to create custom reports focusing on specific parameters, while product trees facilitate the exploration of solution directions, which are documented and saved as options. Although creating reports from scratch demands time and coding skills, adapting existing ones can be done relatively quickly. Once constructed, reports can be reused repeatedly, offering instant updates and feeding the model with computed values for the performance parameters. This exceptional capability of CDP4-COMET to provide transparency in trade-offs is reflected in its assessment, rated as "Excellent."

One of the key lessons from this research is that every tool is unique, and thus the selection must be made according to the project's needs. Capella excels in operational and functional analysis, capturing stakeholder intentions and defining system requirements effectively. However, its effectiveness diminishes in detailed physical architecture implementation. Conversely, CDP4-COMET shines in later design stages, leveraging extensive data integration and robust reporting for effective trade-off management. It offers precise role definitions, data flow controls, and parameter management features absent in Capella's standard version (see Figure 9). It becomes evident that a potential collaboration between both tools, leveraging each for its respective strengths, will lead to superior designs.

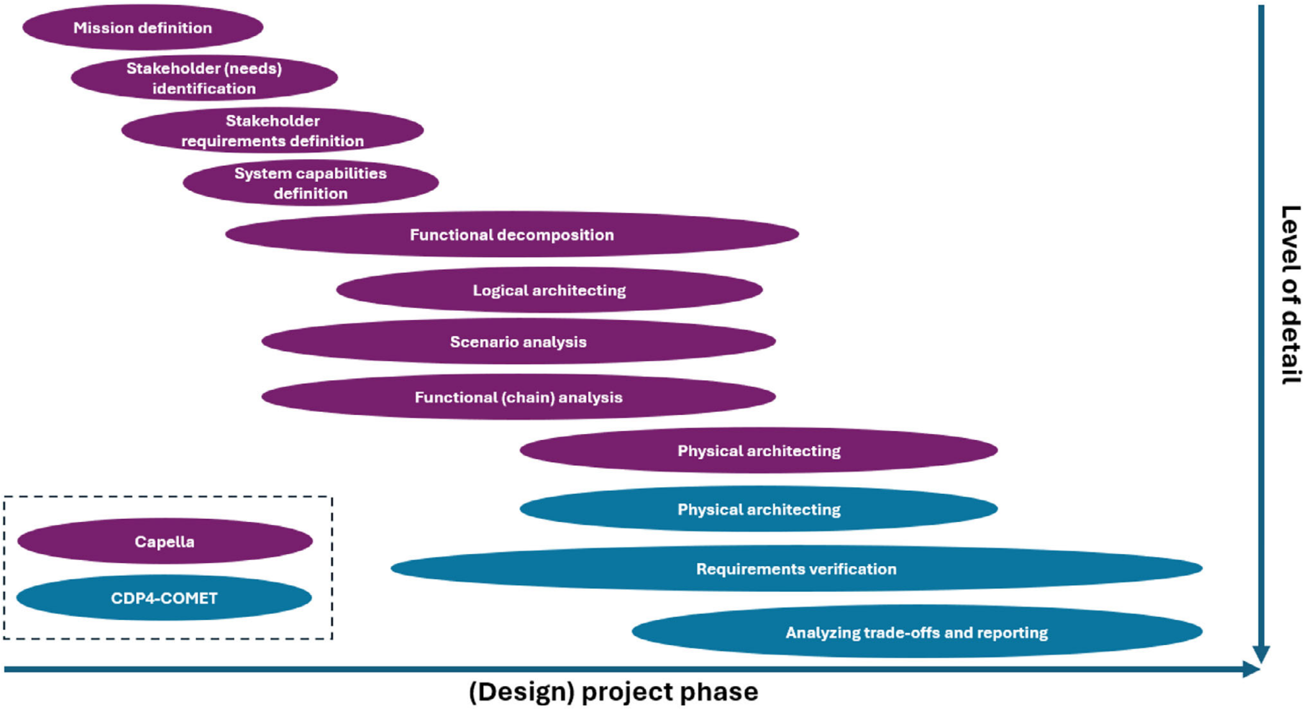

Mission definition
Stakeholder (needs) identification
Stakeholder requirements definition
System capabilities definition
Functional decomposition
Logical architecting
Scenario analysis
Functional (chain) analysis
Physical architecting
Physical architecting
Requirements verification
Analyzing trade-offs and reporting
Capella
CDP4-COMET
Level of detail
(Design) project phase

FIGURE 9 | Visualizing tool proposals across project phases and detail levels (adapted from Kolfschoten et al. [53]).

4.4 | Discussion

The research process provided a framework for addressing the research objective. It covers aspects like mission definition, capability analysis, requirement exploitation, tooling selection, metamodel definition, and systematic system development, ensuring direct links between requirements and architectural artifacts. Focusing on the practical application of MBSE demonstrates value in improving consistency, flexibility, traceability, and trade-offs through well-constructed models. The process maintains simplicity and accessibility while allowing for tool-independent implementation adaptable to diverse systems. It acknowledges the importance of iteration, especially in system architecture development. It emphasizes continuous iteration at both the level of individual process elements and across consecutive steps. However, several limitations in the process stem from utilizing multiple tools concurrently. The methodology lacks clear assessment criteria for precisely rating each tool's capabilities, relying instead on generalized binary compliance, making the rating process subjective. Stringent validation criteria are needed to ensure comparative models accurately showcase each tool's full capabilities, as model quality directly affects perceived tool effectiveness. Additionally, the sequence of model construction can introduce biases, with initial tool selection influencing subsequent models and limiting the exploration of alternative system configurations.

The case study selection aimed to demonstrate the key benefits of MBSE effectively and straightforwardly while laying the groundwork for scaling up to more comprehensive warship designs. Moreover, the decision to study the ship as a whole, rather than focusing on a specific system, was made consciously because it is believed to better represent the challenges encountered during ESSD. Additionally, the metamodel was crucial in ensuring consistency and coherence across modeling activities, providing a shared understanding of design challenges across disciplines and guiding modeling efforts despite the author's sole participation in these activities.

Furthermore, the case study and the comparison between the different MBSE software are positioned to address the steps mentioned in the introduction, aiming at a smooth introduction of MBSE. Specifically, the steps addressed are the demonstration of the value of MBSE and the introduction of MBSE methodologies in a frame familiar to naval architects, while providing a case study that is reproducible for training purposes, as well as compiling a framework that can be used as a guideline in future projects. However, as the naval industry adopts MBSE, the need to replace legacy toolsets and software emerges. For reference, the European Defence Fund has contributed to multiple projects with MBSE at their core [54]. At the same time, the US Navy has already demonstrated with the Littoral Combat Ship class that the requirements need to be set with the entire systems architecture in mind, necessitating a more formalized and holistic approach, like MBSE [9, 55].

Regarding the modeling activities, it is worth noting that the use of CDP4-COMET in this project diverges from its conventional approach, aiming to align more closely with the Arcadia methodology. This adjustment enhanced the consistency between models for a subjective comparison. However, it carries the risk of underutilizing the tool's full potential or not fully exploring its primary strengths. Despite this non-conventional approach, considerable effort was devoted to ensuring that the tool's main strengths were effectively demonstrated. This approach aimed to ensure that the resulting models serve as comprehensive representations of MBSE tools in general, showcasing their capabilities even when used in non-traditional ways.

5 | Conclusions

Several factors contribute to the potential adoption of MBSE in naval vessel design. It is believed that MBSE can accelerate the design process, reduce errors, facilitate the early involvement of industry players, and ensure better alignment between design and requirements. However, its adoption in the maritime industry remains limited due to challenges such as the lack of substantial evidence demonstrating its benefits and confusion surrounding proper MBSE practices. Most existing research is theoretical, focusing on functional and operational architectures, and fails to explore MBSE's value for modern warship systems. The absence of systematic comparisons of MBSE tools further hampers effective implementation, highlighting the need for additional research and practical insights to promote broader adoption in ship design. Considering the challenges inherent in the early design stages of naval vessels, four key requirements for effective design methods were identified: better decision management, adaptability to externalities, novelty and innovation, and the development of a well-structured system architecture. To ensure MBSE has the potential to handle these aspects, it was deemed sufficient to validate the four underlying factors: consistency, traceability, flexibility, and trade-offs.

This paper's principal achievement lies in bridging a research gap by substantiating the practical benefits of MBSE in ESSD. The main objective was to explore and demonstrate the value of MBSE, taking the first steps required for the adoption of MBSE. This was achieved through the implementation of a research process using a hypothetical LPD vessel as a case study. This practical application not only clarified ambiguities surrounding MBSE implementation but also explored the strengths and weaknesses of two prominent MBSE tools.

The assessment of both Capella and CDP4-COMET demonstrated that MBSE tools, in general, can validate the four anticipated benefits. While each tool exhibits unique characteristics and varying degrees of fulfillment for these benefits, the overall findings suggest that MBSE tools can support these fundamental aspects. This overarching conclusion is supported by the fact that Capella and CDP4-COMET are prominent, proven tools in the market. Intensive efforts were made to construct models that effectively showcase the full capabilities of these tools. These efforts aimed to enhance model quality, recognizing its potential to influence the perceived effectiveness of the tools directly and, by extension, the field of MBSE as a whole. The research conducted during the project has demonstrated that MBSE has the capability to enhance and expedite the design process in the early phases of warship design. This was achieved through systematic monitoring efforts and the assessment of results against predetermined success criteria. As a result, it can be concluded that MBSE holds the potential to evolve into a standard operational approach for future naval design processes.

5.1 | Future Work

Future directions for advancing MBSE in ship design include several areas. First, research should focus on preparatory steps and ship-wide metamodels to establish a common understanding and optimal abstraction levels. Additionally, evaluating the costs versus benefits of MBSE implementation is crucial to understanding resource requirements and training intensity. Comparative analysis of various modeling languages beyond Capella and CDP4-COMET will provide a broader perspective on MBSE capabilities. Furthermore, addressing scalability challenges is essential, particularly in managing large-scale data and interactions within IT infrastructures. Integrating multiple MBSE tools into a single source of truth requires further development of tool adapters for seamless data synchronization. Moreover, integrating MBSE tools with existing ship design tools, such as 3D CAD software, enhances their utility across design phases. In addition, enhancing organizational readiness through training and overcoming industry reluctance to adopt innovative practices remains pivotal. This also relates to the need for more industry research and application focused on the unique environment within the naval architecture community to overcome the status quo to get the full value of MBSE into maritime practice. Organizations should focus on improving communication interfaces to facilitate collaboration among diverse stakeholders, including non-MBSE experts, which is essential for advancing MBSE adoption in ship design. Promoting the reusability of MBSE artifacts and leveraging existing designs can optimize development efficiency and cost-effectiveness. In parallel to this, more research should focus on understanding the effect of the reusability of MBSE artifacts on existing designs. Finally, as concluded by Wach et al. [56], MBSE needs a more concrete mathematical and semantical foundation, relating to both the underpinning mathematical methods and the semantic meaning of terms like "adaptability," "robustness," and "flexibility."

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. However, it should be noted that this work was conducted within Starion Group, the developer of the CDP4-COMET software used in the study.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

TABLE A.1 | Example LPD requirements (fictive).

Landing Platform Dock Example Requirements					
Req ID	**Req text**	**Req ID**	**Refinement 1**	**Req ID**	**Refinement 2**
R1	The vessel shall support the deployment of troops and crew personnel	R1.1	The vessel shall accommodate a total of 300 armed troops and 100 crew-personnel		
R2	The vessel must have designated spaces for efficient embarkation, storage, and transportation of supplies, equipment, and amphibious vehicles	R2.1	The vessel shall provide 500 square meters of cargo area for general cargo		

(Continues)

Landing Platform Dock Example Requirements					
Req ID	**Req text**	**Req ID**	**Refinement 1**	**Req ID**	**Refinement 2**
		R2.2	The vessel shall accommodate 35 infantry fighting vehicles with a Ro-Ro area of approximately 1000 square meters and a payload weight capacity of approximately 875 metric tons for vehicles		
R3	The vessel shall ensure swift, secure, and autonomous transfer of personnel, equipment, and vehicles to the AOA	R3.1	The vessel shall maintain a minimum transit speed of 14 knots		
		R3.2	The vessel shall possess a minimum unrefueled transit range of 8000 nautical miles at a speed of 14 knots.		
		R3.3	The vessel shall be equipped with a bow thruster to enhance maneuverability during docking and low-speed operations		
R4	The vessel's dimensions shall be optimized to ensure navigability within designated ports, waterways, and operational constraints	R4.1	The vessel shall have dimensions optimized for navigability, with a maximum draft not exceeding 5.5 meters, a length overall (LOA) not exceeding 130 meters to accommodate port facilities, and a beam not exceeding 22 meters to ensure maneuverability within confined waterways and docking facilities.		
R5	The vessel shall offer amphibious raid flexibility, enabling ship-to-shore movement via landing craft and/or aircraft	R5.1	The vessel shall support ship-to-shore movement via amphibious landing craft	R5.1.1	The vessel shall offer landing craft flexibility, capable of accommodating and deploying 2 LCUAs, 1 LCU, or 9 AAVs as needed
				R5.1.2	The vessel shall feature a well deck with dimensions of L55m x W15m x H6.5m
		R5.2	The vessel shall support ship-to-shore movement via aerial means	R5.2.1	The vessel shall provide a flight deck measuring at least L40m x W20m, capable of simultaneous launch and recovery of two helicopters.
				R5.2.2	The vessel shall provide hangar space for 1 helicopter
				R5.2.3	The vessel shall feature a Helicopter Coordination Section to facilitate safe and efficient coordination of helicopter activities

(Continues)

TABLE A.1 | (Continued)

Landing Platform Dock Example Requirements					
Req ID	**Req text**	**Req ID**	**Refinement 1**	**Req ID**	**Refinement 2**
R6	The vessel should facilitate the efficient loading and preparation of the landing craft or aircraft	R6.1	The vessel shall feature an overhead crane with a capacity of 20 tons for cargo handling operations		
		R6.2	The vessel shall include an aircraft elevator with a capacity of 20 tons to facilitate the vertical transportation of helicopters		
		R6.3	The vessel shall include a Ro-Ro ramp to ensure direct vehicle loading and unloading		
R7	The vessel shall provide emergency rescue capabilities utilizing aerial methods				
R8	The vessel shall be equipped with fire support systems and threat counteraction capabilities to ensure the safety and effectiveness of amphibious operations	R8.1	The vessel shall enable the detection and classification of potential threats	R8.1.1	The vessel shall be equipped with sensors
				R8.1.2	The vessel shall be equipped with automatic systems with identification protocols
		R8.2	The vessel shall be equipped with a Phalanx Close-in Weapon System (CIWS) to provide defense against anti-ship missiles and other close-range threats		
		R8.3	The vessel shall be equipped with decoy systems for self-defense against incoming threats		
R9	The vessel shall maintain habitable conditions for embarked personnel	R9.1	The vessel shall regulate internal temperature for climate control		
		R9.2	The vessel shall ensure continuous airflow for fresh air		
		R9.3	The vessel shall ensure safe and drinkable water supply		
R10	The vessel shall be equipped with an electric plant capable of meeting the vessel's electric demand under all operational conditions				
R11	The vessel shall include a hospital facility with a capacity of 10 beds, equipped to provide comprehensive medical care				

(Continues)

TABLE A.1 | (Continued)

Landing Platform Dock Example Requirements					
Req ID	**Req text**	**Req ID**	**Refinement 1**	**Req ID**	**Refinement 2**
R12	The vessel shall be equipped with communications capabilities, including satellite communication, radio communication, and data transmission systems				
R13	The vessel shall be equipped with surveillance capabilities, including radar systems, sonar systems, and optical sensors, to provide comprehensive situational awareness				
R14	The vessel shall have command and coordination capabilities to facilitate effective leadership and coordination of the operation	R14.1	The vessel shall include an Operations Command Area spanning 400 square meters, capable of accommodating up to 100 military staff		