SE Based Development Framework for Changeable Maritime Systems

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Abstract.
Maritime vessels are complex systems that generate and require the utilization of large amounts of data for maximum efficiency. However, integrating different knowledge and data into the decision-making process during the design process remains a challenge. To address this problem, a development framework to support changeability for next generation vessels is proposed using Model Based Systems Engineering (MBSE) and associated SysML diagrams. This framework incorporates literature and industry interviews and can be integrated into the Systems Engineering development approach to improve decision-making through the inclusion of feedback loops. The contribution of this paper is the establishment of a development framework for incorporating change into the design, development, and deployment of next-generation vessels.

Keywords: Systems Engineering, Model Based Systems Engineering, SysML, System Development, Changeability, System Architecture, Extended Value, Maritime

1 Introduction

The maritime industry faces a variety of challenges related to sustainability (changing international environmental regulations), automation, and global economic conditions. So, while pursuing sustainability is important for the long-term health of our planet (reducing the carbon footprint of the industry through decreased reliance on fossil fuels), it often comes at a cost that must be carefully balanced with economic and social considerations. Designing for Changeability (DFC) is one approach that can become essential for meeting technological advances, changing regulations, and shifting customer demands [1]–[3]. By being agile and adaptable, maritime vessels can take advantage of opportunities to better serve the needs of the customers and stakeholders and thus be more capable of adapting to changing requirements and environments [4], [5]. The ability to meet such events proactively can extend the life of the vessel by delivering value irrespective of when/where changes occur [6], [7].

To address this challenge, this paper proposes a conceptual framework that leverages systems engineering to support the design of changeable maritime vessels. The guiding question for this research is what should be considered during the design process for changeability to be realized in maritime vessels. The framework incorporates literature and industry interviews and can be integrated into the maritime development process to future proof and extended value of vessels.

1.1 Research Approach

A three-stage methodology was utilized for this study, consisting of a literature review, focus group, and a conceptual case. To identify the most relevant literature, SCOPUS, a database for academic literature, was used to search for literature pertaining to maritime vessel design, systems engineering, and changeability. The literature was collected using keywords (changeability, maritime vessel change, maritime vessel life cycle design, maritime ship design process) and filtered based on their field (Engineering), document type (paper & article), and language (English). Subsequent filtering was performed according to field of interest and the manuscript abstract.

A focus group was conducted with ten individuals (across 5 EU countries) involved in the design, construction, and testing of maritime vessels to identify and define changes faced by maritime vessels. The participants had an average of 6 years of work experience. Semi-structured interviews were conducted to discover precise insights of the actual vessel development process, particularly for aspects related to changeability, techniques to predict lifecycle operational contexts, etc. Each participant was asked to describe the most impactful changes that could be implemented to a current design to extend value according to modified stakeholder expectations. The combined expert opinions and literature findings were used to identify critical design considerations, and strategy's for implementing changeability into maritime vessels.

2 Approaches to Maritime Development

Maritime vessel design is a complex, iterative and multifaceted process, influenced by a number of internal and external factors [1], [8]. Depending on the vision or requirements set forth by the customer, designers are tasked with developing cost-efficient vessels capable of performing specific tasks, while adhering strictly to both international and national rules and regulations.

- **Concept Design** has the greatest impact on all subsequent stages, such as detailed design and construction. The aim is to define the ship's basic characteristics, such as type, deadweight, type of propulsion, and service speed, without requiring detailed calculations to be performed [8]–[10].
- **Preliminary Design** phase concerns the definition of the ship contract, as well as the completion of the maritime vessel's performance characteristics [9], [10].
- **Basic Design** phase involves a refinement process for the maritime vessel design, including the extension of the initial design to ensure ship performance characteristics, refinement of the general agreement (between the ship owner and the shipyard), basic design of the hull, and arrangement of ship systems (such as propulsion and electrical systems) concluding with a general production plan [9].
- **Detailed Engineering** begins with the creation of detailed material for maritime vessel hull production, as well as material procurement-related activities (such as ordering materials and equipment needed for the ship's construction) [9], [10].
- **Commissioning and Warranty** confirm the functionality of a technical system and obtain operational assurance. Technical assistance is provided during the production and warranty phases when the ship is sold. Feedback is collected during these phases to prevent possible system malfunctions and failures [11].

2.1 Design Spiral

The type of vessel design has a strong influence on the design choices and process, which is undertaken from conception to final customer delivery. This is due to both customer expectations and legal rules/regulations. The most common vessel design process is the spiral design process, which is often used in the shipbuilding industry [9], [12]–[14]. The 'Ship design spiral' is one of the most commonly used approaches to development and employs a sequential and iterative process [9], [15], [16]. The first step of the spiral design process is to establish requirements, which is a fundamental starting point before entering the concept design phase. This leads to preliminary power estimations, a propulsion system, hull shape, and preliminary cost estimations. Within each phase, solutions become more specific, and options are set, culminating in a design that is ready for authorization. The spiral does not involve exploration of potential solution variants, it relies on point-design making it well suited for the detailed phases but restrictive during the preliminary and conceptual phases.

2.2 Systems Engineering

Systems Engineering (SE) is "an interdisciplinary approach and means to enable the realization of successful systems by defining stakeholder needs, required functions, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: operations, performance, testing, manufacturing, cost & schedules, training & support, as well as system disposal [17]." This approach has become increasingly relevant and important with the increasing complexity of modern vessels, as it provides engineers with a structured and formalized way to integrate new design elements for the creation of unprecedented systems. It also strengthens communication in the design process. By taking a systemic development approach, SE facilitates the decomposition of the system, which improves the ability for engineers to analyse technical and non-technical parameters. This effectively allows for requirements to be balanced and analysed in greater detail, which is critical for the development of unprecedented or complex systems. The emphasis on decomposition and analysis enables data-driven decisions to be incorporated into every stage of development and provides a means for testing and validating capabilities.

In the ship design process, systems engineering is a critical component that helps to ensure that the various systems and components of the vessel are integrated and work together seamlessly [2], [18]. By taking a holistic approach to ship design, systems engineering helps to identify potential conflicts and trade-offs between different systems and ensures that the vessel meets the specific needs of its intended use. This approach is particularly important for maritime vessels, which must meet a wide range of requirements, including speed, manoeuvrability, and emissions. Additionally, systems engineering helps to manage the complexity of modern vessels, which have become increasingly reliant on advanced technology. By using systems engineering principles, designers can develop vessels that are not only reliable and efficient, but also easier to operate and maintain. This can reduce costs and improve the overall effectiveness of the vessel. Overall, systems engineering plays a vital role in the design and construction of modern maritime vessels and has become increasingly important as vessels have become more complex and sophisticated.

2.2.1 Model Based Systems Engineering

Model-Based Systems Engineering (MBSE) is a formalized application of modelling that supports system requirements, design, analysis, verification, and validation activities [17]. Its use of digital models to simulate complex systems has revolutionized the way we approach engineering design and optimization.

In the maritime industry, MBSE has emerged as a powerful tool for designing and optimizing complex ship systems. By using modular computer-based design tools and model-based design, MBSE facilitates concurrent design, analysis, and optimization processes, resulting in cost-effective and shorter design cycles. MBSE has been particularly effective in the maritime industry is in the design and optimization of propulsion systems. By creating digital models of the propulsion systems, designers can simulate the behaviour of the system under different conditions and optimize its performance. This has led to significant improvements in fuel efficiency, reducing the environmental impact of shipping. MBSE has proven to be a valuable tool for designing and optimizing complex systems in the maritime industry. Its application has resulted in significant improvements in cost-effectiveness, efficiency, and environmental sustainability. As such, it is an area of research that warrants further exploration and development.

3 Changes Impacting System Value

Change is unavoidable in both reality and perception, as such when the life span of a system is extended the number of changes encountered increases. Consequently, the value of the system is a key consideration when any engineering design decision is made to accommodate or enable a potential change. Changeability seeks to enhance/sustain/maintain the value of a system throughout its lifecycle by either increasing the systems technical performance or reducing the cost of recursive changes that diminish system value. This requires the control and the management of mismatches between system offerings and stakeholder expectations, including responses for dynamic changes (initiated, emergent, or propagated) as shown in Table 1 [7], [25].

Table 1. Classification of Value Diminishing Changes

Example of Change Reducing Value	Type	Initiator	Mech.
Advances in technology: Incorporation of new materials, components, techniques, or processes (advances in the state-of-the-art) not available at the time of the initial design effort.	Initiated Change	Ext. Tech. System	Sub.
Excessive cost: Prior design proved technically adequate, but subsequent cost analysis revealed excessive cost.	Emergent Change	Int. Tech. System	Sub.
Questioning specifications: User's specifications are questioned, determined to be inappropriate, out-of-date, or over specified.	Emergent Change	Int. Tech. System	Add. /Rem.
Additional design effort: Application of additional skills, ideas, and information available but not utilized during design effort.	Emergent Change	Int. Tech. System	Add. /Rem.
Change in user's needs: User's modify or redefine of mission, function, or application of item.	Propagated Change	Int. Tech. System	Mod.
Feedback from test/use: Design modification based on user tests or field experience, parameters governing previous design.	Propagated Change	Int. Tech. System	Mod.
Design deficiencies: Prior design proved inadequate (e.g., characterized by inadequate performance, excessive failure rates, etc).	Propagated Change	Int. Tech. System	Mod.

Table 1 presents a synthesis of changes identified by the US Defence Logistics Agency, and the Society of American Value Engineers (reviewed 415 implemented changes), as well as adjacent maritime literature on engineering changes to identify types of change that can reduce the value of an engineering system [19]–[22]. The changes are classified according to the change type, agent/initiator responsible [23]; activation/realization mechanisms used [24], [25]; Modification (change in components or interface), substitution, and addition/removal.

4 SE Based Changeable Framework for Maritime

The framework takes inspiration from the Win-Win and Theory-W approach to decision outcomes, which emphasizes that for an outcome to be value-creating (positive), everyone in the process needs to be a winner. This people-process centric concept allows the human and technological elements of engineering to encourage communication, integration, and knowledge sharing among its stakeholders to facilitate more effective vessel design. The framework serves as an adjustable complementary element to be built into the concept design phase of maritime vessels to facilitate the integration and consideration of value enhancing change.

This risk mitigating and cost-conscious approach to the integration of DFC increases and extends the value of a vessel. Allowing for change to be value positive, whereby the introduction of change to a vessel leverages the evolutionary nature of ship building and supports future technological adoption and digitalization. This encourages architects and ship designers to apply design rules, standards, and instructions to produce a design that ensures sufficient design margins so that problems of the past will not reoccur, while future problems can be mitigated.

4.1 Articulation Phase

The first step involves determining the scope and boundaries of the system, identifying the stakeholders and their needs, defining the system requirements and functions, evaluating the feasibility of the system design, establishing criteria for success, potential risks and mitigation strategies, strategy to support DFC and necessary design margins. The enables conceptual separation between elements within the system and its environment [25], [27] and can have overlap with Concept of Operations (ConOps) and Operational Concept (OpCons) documentation [26].

- **Usecase Diagram** is used to identify the different actors (users, systems, or external entities) that interact with the system and the different use cases (functions or services) that the vessel provides to each actor. For a changeable vessel, the use case diagram could identify different actors that interact with the vessel, as well as additional factors that are related to the use cases (navigation, communication, cargo handling, and passenger services).
- **Context Diagram**: The context diagram represents the vessel and relationships with external entities such as ports, other vessels, and weather systems as inputs and outputs. The diagram could also show different interfaces between the vessel and the external entities, such as the communication and navigation systems.
  - **Type of voyage** (intended use). Refers to the number of passengers, number of crew members, the number of onboard passenger vehicles, freight mass.

  - The **operating environment** areas in which the vessel will operate throughout its life cycle. Which includes environmental conditions such as: wind speed, wave height, wind force, fetch size, and water depth.
  - **Operating duration** that the vessel will be used for in the expected environment, which corresponds to the voyage and stakeholder requirements that include cruising speed, nautical coverage, fuel autonomy, and energy demand.
  - **Emissions regulations** for the operational context (geographical area + operating duration) to be addressed during vessel's lifecycle.

4.2 Prioritization Phase

Once the system has been identified, the next step is to develop and prioritize a set of requirements that the system must satisfy. The phase supports cognitive and team capabilities ensuring that all persons understand the needs and can effectively describe the value of the vessel in terms of capabilities, performance, function, and costs.

- **Requirements**: Functional, non-functional, technical, and mission requirements for the system to determine levels of correspondence based on clusters and the elements within the system boundary. Design margins and DFC can be utilized to manage uncertainty associated potential changes. Based on the heuristic ranking of elements the impact and bond between element and requirement demonstrate the understood priorities of the system designers [28].
  - **Requirements Diagram:** Is used to capture and organize the different requirements of the system. This can include both functional and non-functional requirements, as well as requirements related to performance, reliability, safety, and other factors.
  - **Sequence Diagram**: Models the interactions between different objects or components in the system. During the requirements process, designers should consider the potential for future changes or upgrades to the system and ensure that the requirements reflect this. This may involve identifying potential areas for modularity or standardization or considering how the system's layout can be made more flexible. This helps to identify the requirements related to system communication and data exchange.
  - **Traceability Matrix:** Is used to link the elicited vessel requirements to other model elements, such as system components, design elements, and test cases. This allows for the tracking of relationships between requirements and elements throughout the design process. The matrix can be leveraged to track changes made to alter the state of the system, including running tests to measure performance, functionality, or other key metrics. If the change has a negative impact, it may reduce the value of the system.

It's important to note that a poorly articulated system can cause the prioritization phase to fail, resulting in an ineffective architecture to the be designed. The stakeholder's involvement in the development process is crucial for the success of the framework. Even if the team assumes the system is well-defined, deviations from critical needs and ilities can cause significant problems. Therefore, the team should compare each relationship against one another to avoid loose understanding.

4.3 Evaluate

The evaluation phase considers the system elements and represents the general architecture of system and its components. This considers the relationships between the different elements/components and how they interact with each other.

- **Coupling within the system**: Coupling describes how closely related/connected elements and components of the system and how much they rely on each other to perform properly (tightly coupled, vs loosely coupled) [30]. Tight coupling is when components are highly dependent on one another while loose coupling is when there is little or no dependency between components. The differences between tight and loose coupling can also be described in terms of coordination and information flow. Within vessel design coupling can make the system more (loosely coupled systems) or less changeable (tightly coupled) due to the potential of propagated change, and difficulty predicting the full impact of changes.
    - **Block Definition Diagram**: Enables the definition of the system architecture in terms of blocks (system components) and their relationships. For a changeable maritime vessel, the blocks might include the hull, propulsion system, navigation system, and/or communication system.
    - **Internal Block Diagram**: Can be utilized to model the internal structure of each block and how its parts are interconnected. In this context, the model could be used to show the internal components of the propulsion system and how they are connected to the hull.
- **Solution viability and testing**: Determining viability involves assessing whether a solution, despite meeting stakeholder needs, is feasible given the complexity, changeability, and organizational/institutional factors. Equally important is testing to validate that the system can deliver the functions designed according to stakeholders' needs. The evaluation of system viability is based on determining whether a system is suitable for adopting or implementing DFC. Although all systems have the potential to be changeable, not all are well-suited, and not all changes or design solutions provide the most value to stakeholders. To determine suitability the change effect, cost, effort, and life cycle implications (extending/reducing the possibility for additional value enhancing changes).
    - **Activity Diagram**: The flow of activities within the vessel enables for the operations and maintenance actions of the vessel, and to understand how specific changes (parametric diagram) effect the system. This could include activities such as starting and stopping the engines, raising, and lowering the anchor, or adjusting the sails.
    - **State Machine Diagram**: The diagram is used to model the behaviour of the vessel in different states (the events that cause it to transition from one state to another), such as cruising, docking, or manoeuvring.
    - **Sequence Diagram**: Is used to model the interactions between different blocks or systems over time.
    - **Parametric Diagram**: Is used to model the relationships between system parameters, such as inputs, outputs, and constraints, as well as analyse the impact of changes, and the effect of the change on the overall system.

4.4 Reveal

In the concept design phase, the reveal process provides an opportunity for feedback and design review from all stakeholders. The process considers and leverages multiple models previously described to ensure the vessel meets the requirements and needs of the stakeholders. Using the system models developed, the current state of the system can be compared against various changes to demonstrate technical, performance or functional value increases. This model can be used to communicate the changes to stakeholders and get their feedback on whether the changes will provide value. The model can also be used to identify any potential issues or conflicts that may arise as a result of the changes.

- **System:** To ensure that a change made to the system provides value, the models can be used to simulate the behavior of the system before and after the change. This simulation can be used to test the impact of the change on the system and identify any potential issues or unintended consequences. By simulating the behavior of the system, you can ensure that the change will provide the desired value without negatively impacting the system.
- **Effect**: The evaluation of the change (current vs future state) allows for direct comparison of the action and helps to verify if the respective process can handle/manage the change according to the boundaries and considerations established. The updated model is used to analyse the impact of the change on the system. This can involve simulating the behaviour of the system before and after the change to identify any potential issues or unintended consequences.
- **Cost/Effort:** Through the comparison of the models and analysis of the impact of the change, an estimate can be made of the effort required to implement the change. This may include estimating the amount of time required to modify the system design, update documentation, and test the modified system. Once the effort is estimated, the cost can be calculated (labour, materials, equipment).

4.5 Update and Implement

Due to the inherent complexity of maritime systems once the changes are evaluated and compared, the system must return be revaluated using the models previously developed (Section 4.1 - 4.3).

- **Update**: The process for system update, takes the results generated from the reveal and evaluation process to improve the placement and allocation of within the system according to the evaluated elements and relationships. The update phase introduces a series of processed adjustments to the system before passing to the detailed design phase. This includes verification of the system, changeability, testing documents, design, and functionality. It includes activities such as inspection (measurement to verify the system elements conform to its specified requirements), analysis (the use of established technical or mathematical models or simulations, algorithms, or other scientific principles and procedures to provide evidence that the changeable system meets its stated requirements), and demonstration (actual operation of an item to provide evidence that it accomplishes the required functions under specific scenarios).

- **Implement**: The implementation phase serves as an authentication and engagement step according to feedback from the critical design review (reveal). This determines how the change should be incorporated into the system and must be performed in a concurrent manner. Implementation occurs through the following actions: (1) Define how the change will be integrated into the design based on the model diagrams, (2) Ensure the critical tests and outputs support value extension, and (3) Ensure the change in not in conflict with the system functions.

4.6 Execute

The execution phase is enacted according to the knowledge, value, and cost prioritization measures of the system to mitigate risk [32], [33]. Based on the outcomes derived during the concept development phase the requirements, interactions and functions must be reviewed and validated, reducing backlash.

5 Concluding Remarks

The presented conceptual framework cannot be applied without intense collaboration between shipbuilders and customers. This collaboration is crucial for the maritime industry to overcome its biggest challenge: customers sending their technical requirements directly to the company without allowing for a more profound collaboration. This approach leaves the customer less aware of the risks they may face without having a vessel designed for changeability, such as the inability to operate in the future due to emissions rules or the excessive cost of change. On the other hand, the shipbuilder does not have a deeper understanding of the customer's future needs or support in technology forecasting and related change-ability design choices. Therefore, a cultural change is necessary to allow design thinking principles to truly impact the development process, involving both customers and shipbuilders.

This study has contributed to the development of a specialized conceptual framework that can help maritime engineers and architects design changeable maritime vessels. The preliminary outcomes derived have helped validate the framework and have shown how a greater reliance on digital modelling tools could be used to improve the decision-making process.

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