AN SE BASED MARITIME VESSEL DEVELOPMENT FRAMEWORK FOR CHANGEABLE PROPULSION SYSTEMS

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ABSTRACT

Reducing Greenhouse Gas Emissions from vessels is one of the greatest challenges the maritime industry is currently facing. International Maritime Organization has set the goal of reducing CO2 emissions from international shipping by at least 40% by 2030, compared to 2008. Emissions regulations are also leading to a progressive reduction of ships life span, together with a decrease in economic value. To cope with these challenges, the preferred strategy suggested by IMO for new vessels -Energy Efficiency Design Index- aims at increasing the energy efficiency over time by stimulating innovation and continuous development of technical elements. In this context, ship builders are indirectly led to develop vessels that will be "changeable" in terms of propulsion systems over time. This paper presents a conceptual framework to maritime vessels for propulsion system changeability, which integrates contributions from literature review with the knowledge of design thinking experts and precious insights of maritime industry professionals. The aim of this framework is support the integration of renewable fuel sources for vessel propulsion systems through an extended value approach, while improving propulsion efficiency over time.

Keywords: Design for X (DfX), Conceptual design, Sustainability, Changeable Propulsion System, Design methodology

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Cite this article: Sullivan, B., Rossi, M. (2023) 'An SE Based Maritime Vessel Development Framework for Changeable Propulsion Systems', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.56

1 INTRODUCTION

The maritime industry has always been a critical factor both socially and economically. When Designing maritime vessels is a complex process due to a variety of factors, including the vessel's expected lifespan, the cost of construction and maintenance, the complexity of the vessel's systems and components, and the potential impact of changes to the design during construction or operation. These factors must be carefully considered and balanced to create a vessel that is safe, efficient, and cost-effective. However, irrespective of the detail and effort to plan for every possible circumstance, change is inevitable, the perception of a system's value will continually change throughout its lifecycle (Beesemyer et al. 2012). This includes changes to the system to reduce the environmental impact from emissions (scrubbers), adoption of green technologies (LNG, LH2, GH2) or the modification of other critical system functions that can improve the efficiency of the vessel throughout its lifespan time (Sullivan et al. 2022).

Changeability seeks to extend the value of a system irrespective of changes introduced, irrespective of time (Mekdeci et al. 2015). Changeability has been identified as a valid approach for maritime development, particularly in the development of vessels that operate in environmentally protected areas or can be subject to emission reduction legislations (IMO 2020 sulfur cap, Energy Efficiency Design Index, Ship Energy Efficiency Management Plan). In response to environmental legislation and regulations, ship builders are currently faced with choosing from an abundance of propulsion technologies (Diesel, Hybrid, LNG, LH2, GH2, etc.) which are either high polluters (SOx, Nox, CO2), in development, or with limited range. Accordingly, there is a need to develop vessels that can change quickly and easily to preserve and extend the value of the vessel.

Despite the increasing amount of information and data related to vessel operations, a challenge remains in how to leverage this information in the most efficient manner during the design, maintenance and operation life cycle phases of maritime systems. The rationale for this work is due to the absence of a design framework that allows for propulsion system changeability, since once the hull and many other aspects of the system are developed there are limited changes that can be incorporated at a future time. This served as the motivation for this paper and the propulsion system changeability design framework introduced. In an effort to facilitate and increase the competitiveness of the Global maritime industry, lessons learned from the naval and specialized vessel industry have served as key elements in the development of the proposed framework. Through a literature review of changeability and the design process, interviews with shipyards and vessel designers (maritime engineers and naval architects) were performed in order to merge design thinking (requirements elicitation) and changeability (concept development phase) into propulsion system design. This paper concludes with a group of enablers and guidelines to be implemented during the concept development phase, that can positively increase design margins during the design process and extend the life cycle value of maritime vessels.

2 METHODOLOGY

A two-step methodology was adopted for this study, combining literature review and focus group research. The State Of Art (SOA) review for changeability and design margins was performed utilizing Scopus. The SOA findings and focus groups research have been conducted to gather all relevant knowledge to formulate the conceptual framework.

2.1 State of the art - literature review

To analyse literature contribution in terms of changeability, two main databases were selected: Scopus and Google Scholar. The articles were filtered based on their field (Engineering), document type (paper & article) and language (English). Subsequent filtering was made for keywords and field of interest, resulting in the identification and analysis of 174 documents. Changeability has been defined as an “umbrella term for several change-related ilities” (Colombo et al. 2016), with four main lower-level ilities related: flexibility, robustness, adaptability and agility. In conceptualizing value enhancing change the motivation for the change is reflected as externalities (dynamic marketplace, technological evolution, variety of environments and policy), while the type of change enacted (initiated, emergent, and propagated) (Schulz and Fricke 1999; Sullivan et al. 2018). The potential for the change to be enacted is highly related to the

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design margins (capacity or capability that is included in the design) and ultimately determines which changes can be effectively made to positively extend the systems value (Brahma et al. 2022).
In order to complete the SOA, research in fundamentals of ship design was performed, highlighting the main process steps, design methodologies (Harvey and Evans 1959), and parameters that influence vessel propulsion efficiency and emissions generation.

2.2 Focus group research

In order to overcome gaps found in the SOA, Focus Groups research was used to gain the right mix of creativity and flexibility that is required to gather the necessary information. This research was conducted first with a panel of design thinking experts at Centre for Design Research Stanford University to identify an effective strategy for requirements, and then with a group of international experts involved in ship design and construction. The former contributed to understand how design thinking principles could be integrated into the vessel design process, and to evaluate enablers for propulsion system changeability. The interviews with maritime experts provided insights into the actual vessel development process -particularly for aspects related to changeability, and current techniques to predict future lifecycle operational contexts. Combining these insights the authors were able to verify enablers for maritime propulsion systems changeability and discover ways to implement design thinking principles in different contexts.

3 CHANGEABILITY AND MARITIME DESIGN

The most relevant aspects resulting from SOA have been the general concept of changeability –with the underlining theory and applications–, the general development process in the ship building industry and the interactions between these two pillars. These concepts will be presented in the following sub-chapters to explain their importance and impact on the proceeding conceptual framework (Section 4).

3.1 Changeability overview

All systems aim to provide some level of value to stakeholders occupying or utilizing a system throughout its life cycle, changeability as a concept aims to extend the value of the system by enabling and supporting changes to take place (Mekdeci 2013). As a high-level system ility changeability can be broadly understood as the ability of a system to change form, function, or operation, according to lower-level system ilities such as flexibility, agility, adaptability, evolvability, upgradeability, and versatility. Subsequently lower-level ilities refer to the theoretical and applied notion of change within the system (Colombo et al. 2016), determining not only what is changing, but also how changes are enacted throughout the system (McManus et al. 2007). These lower-level system ilities include but are not limited to adaptability, flexibility, robustness, and resilience.
In this context "changeability" refers to the ability to make changes or modifications to a system that has extra capacity or tolerance built into the design to account for uncertainties or potential changes (Uckun et al. 2014; Colombo et al. 2016; Sullivan et al. 2019; Brahma et al. 2022). The relationship between changeability and design capacity (design margins) is that having larger design margins can make a product or system more changeable. This is because the extra capacity or tolerance built into the design provides more flexibility to make modifications without compromising the performance or safety of the product or system. On the other hand, if design margins are narrow, any changes made to the system may have a negative impact on its performance or safety, making it less changeable due to propagation of the change (coupling).

3.1.1 Design margins and system coupling

Design margins and system coupling are both important considerations in system changeability, as they can have a significant impact on the performance and reliability of the system. Design margins refer to the amount of extra capacity or capability that is included in a design beyond what is strictly necessary for it to function properly (Eckert et al. 2019; Brahma et al. 2022). This extra capacity can be useful in a variety of ways, such as allowing for future upgrades or modifications, accommodating unexpected changes in operating conditions, or providing a safety buffer to prevent catastrophic failure.
System coupling refers to the degree (tight vs. loose coupling) to which different components or subsystems within a system are interconnected or interdependent (Chhabra and Parashar 2014; Valerdi and Sullivan 2020). In some cases, tight coupling can be beneficial, as it can improve the systems

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efficiency and performance. However, tight coupling can also make a system more vulnerable to failures or disruptions when a change is introduced in one part of the system since it can easily propagate to other parts.

Design margins and system coupling can be viewed as being interrelated, as the amount of extra capacity built into a design can affect the degree of coupling between different components or subsystems. For example, a highly integrated engine and propulsion system can result in better fuel efficiency and smoother operation, though even a small change or disruption can have a significant impact on system performance. On the other hand, if the propulsion system is designed with generous margins and built-in redundancies, it may be more resilient to disruptions and less susceptible to the negative effects of coupling. Overall, managing the right balance between design margins and system coupling is an important consideration in design changeability, as it can affects both the reliability, resilience and adaptability of the system.

3.1.2 Change types

All changes can be seen as both threats and opportunities depending on the margins and coupling of the system. On one hand, changes can increase the amount of rework and can lead to additional changes, thus increasing costs and effort; on the other, they offer the chance to improve the system, increasing the performance, providing useful functionalities or reducing undesired features (Jarratt et al. 2011). Considering the premise of changeability and relationship to design margins and system coupling the following types of change are considered:

- Initiated Change: Can be a planned (anticipatory action) or unplanned (in response to) action that is generated from outside of the technical system by either an internal or external agent (Mcmahon 1994; Fricke et al. 2000; Altenhofen et al. 2015). With such types of change it is important to consider the impact that the changes will have on the system and the relevant design margins. If the change overly reduces the margin, the system may become vulnerable to failure or under performance (reducing the overall value of the system).
- Emergent Change: Are generated from within the technical system in response to "problems occurring across the design" (Ross and Rhodes 2008) by either an internal or external agent. By designing with margins, engineers can ensure that the system has the capacity to adapt to changing circumstances without compromising its overall performance or safety. However, it is important to strike a balance between having enough margin to accommodate changes and not over-designing the system, which can lead to unnecessary costs or complexity.
- Propagated Change: Are changes that occur due to other changes within the technical system (Giffin et al. 2009). By designing margins into the system, engineers can better ensure that the system remains reliable and robust in the face of unexpected changes.

3.1.3 System externalities

Even the best project planners and systems engineers cannot account for every unforeseen possibility (Ross, Rhodes and Hastings, 2008). By incorporating socio variables into the design and planning stages, not only are limitations able to be transferred into design variables but also aid in the design of a system that is able to operate beyond its initial environment. Socio variables have been considered as critical impact factors in systems engineering since the 1970's. Based on the work of Fricke such dynamic pressures and changes being encountered in system development can be viewed in three distinct domains: the dynamics of the marketplace, technological evolution, and variety of environments (Fricke and Schulz, 2005). The literature supported adding dynamic regulations to the three dimensions presented by Fricke (Sullivan et al. 2018).

- Dynamic Market: market pressures require the development of systems able to deliver active value while maintaining a high level of responsiveness in terms of supporting design changes to reduce the time gap between design freeze and system delivery.
- Dynamic Regulations: represents rules mandating system behaviour.
- Technological Evolution: the ability to meet specific market and needs requires the ability to efficiently change the system to accommodate new, novel technologies (which can be unpredictable). Technology influences all aspects of the system and is an enabler for new and advanced systems (Fricke et al., 2000).
- Variety of Environments: may be indicated by the number of embedded systems, integration of diverse technologies, or number of operational contexts (Mekdeci, 2013). Interrelated elements

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and embedded system can be impacted by all changes placed upon the system and are affected by the evolution of technology (Ross and Rhodes, 2008a).

3.2 Maritime vessel design overview

Ship design is characterized by a high degree of complexity and must take into account a wide range of factors, including the intended use of the vessel, the environment in which it will operate, safety regulations, and the materials and technologies that will be used in its construction (Vossen et al. 2013). Accordingly, the following synthesized phases represent the general process for vessel design (Misra 2015; Sahoo 2021)

- Concept Design has the greatest impact in all the subsequent stages. Its main aim is the definition of the ship basic characteristics, such as type, deadweight, type of propulsion and service speed, without the need of detailed calculations.
- Preliminary Design is important for the definition of the ship contract, as well as the completion of the main ship performance characteristics. In this phase technical material for tender and contract is created, design and material cost for the ship project is estimated, and quantitative calculations are done to support production planning and sales support in technical issues.
- Basic Design phase begins a refinement process, involving the extension of the initial design to ensure ship performance characteristics, the refinement of the general agreement, the basic design of the ship hull and ship systems arrangements. Other important activities involved in this step are also routing and space reservations, and from the client perspective the approval of the technical documents with customer. After that, there is the preparation of plans, guidelines, lists of standard solutions needed for the detail design engineering.
- Detailed Engineering begins with the creation of detailed material for hull production, together with material procurement-related activities. Supporting the assembly to make the ship detailed design effective.
- Commissioning and Warranty phase is important to confirm the technical system functionality, obtaining the operational assurance. Then, technical assistance is provided for both production phase and warranty, when the ship will be sold, with feedback collections to prevent and face possible malfunctions and failures of the system (Universtiy 2016).

3.2.1 Ship design methodologies

Ship design methodologies frequently rely on tradition and historical reference models. The most significant approach is the “Ship design spiral” by Evans (Harvey and Evans 1959). This method is a sequential and iterative process, intended to be adopted to deal with complex systems where it is difficult to directly understand the relationship and possible interactions between function and form. The steps included in the spiral have a deeper level of technical details such as machinery, displacement and trim, resistance and propulsion, stability, form coefficients and hull lines. The spiral is well suited for the detailed phases of the design process, more so than the preliminary or conceptual phases. Furthermore, the spiral as presented by Evans does not involve exploration of potential solution variants but relies only on the point-design iteration to generate an actual feasible solution. Consequently, Evans’ spiral has been often criticized for locking the designers to their first assumptions.

An evolution of this methodology was suggested 1981, when Andrews introduced the Creative Ship Design methodology. After having reviewed various contemporary design methods, the author concluded in fact that there was a lack of methods that provided tools for generating radically new designs. He proposes then two steps towards a more creative ship design process. The first is an outline for how Computer Aided Architectural Design (CAAD) can be leveraged to explore the internal ship layout and the complete ship form. The second is regarding how design techniques can be used to produce an open and creative philosophy. This can be seen as an evolution of the first proper design spiral introduced by Evans, with the intent to solve the creativity criticalities emerged in that model. The ship design process may be in this model broken down broadly into two stages: conceptual and/or preliminary design and detailed or tender or contract design. The preliminary design process will normally take the form of a techno-economic assessment, using a fundamental engineering economy approach. The ship owner's operational requirements need to be established during preliminary designing, which then allows the development of a basic specification such as deadweight, speed, range, capacity, stability, and freeboard. Throughout all these phases, it was found that that propulsion system, hull design and materials have yet from the first phases a huge consideration: these

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components have in fact the greatest potential impact on ship energy efficiency (gCaptain, 2019). Nevertheless, thinking about future upgrades to increase energy efficiency, only the propulsion system could be upgraded, resulting the only key design alternative to be considered for changeability.

3.3 Changeability in ship design

Changeability in ship design is a relatively new research trend, with most publications being related to the application of already existing models to identify possible future contextual developments and evaluate alternative system designs in terms of physical and economic performances. Gaspar used Epoch-Era Analysis method in order to identify possible future contexts for a vessel, connecting contextual uncertainty to changeability (Gaspar et al., 2012). Rehn et al. used a combination of EEA method with Monte Carlo simulation in order to access the trade-off of versatility vs. retrofitability, that is to say passive ways of achieving value robustness versus active ones (Rehn et al., 2018). In another paper, Rehn et al. used then the Tradespace Representation of a system in order to investigate trade-offs between technical performances, costs and flexibility level for a reconfigurable ship (Rehn et al., 2018). Rehn also investigates how to quantify Changeability level, with two main approaches: the bottom-up starts from estimating the reduction in cost and time of change in order to quantify changeability level, while the bottom-up analyses the number of configurations that could be changed (upgraded) at a given cost and time (Rehn et al., 2019).

4 CHANGEABILITY DEVELOPMENT FRAMEWORK

The purpose of the conceptual framework is to provide an approach to help ship builders in designing vessels for propulsion system changeability, in order to better manage uncertainty and challenges related to propulsion system design and planning. The ultimate aim is to define active ways to increase vessels value robustness over time, contributing to close the literature gap in terms of changeability in maritime industry and related applications. In particular, the framework focuses on the concept and preliminary design phases, since it was concluded from the literature and focus group that these two phases are the most impactful in terms of leveraging and incorporating changeability.

4.1 Changeable maritime propulsion system design framework

In an effort to achieve the aforementioned goals and aims while developing the conceptual framework, the process has been divided into sections. The first one includes a set of guidelines to identify the preliminary changeability requirements to be included at the beginning of concept design phase and is the section that presents the most the design thinking philosophy. The second part of the framework instead identifies which are the high-level implementation guidelines to facilitate the inclusion of maritime propulsion systems changeability principles yet from the concept design phase.

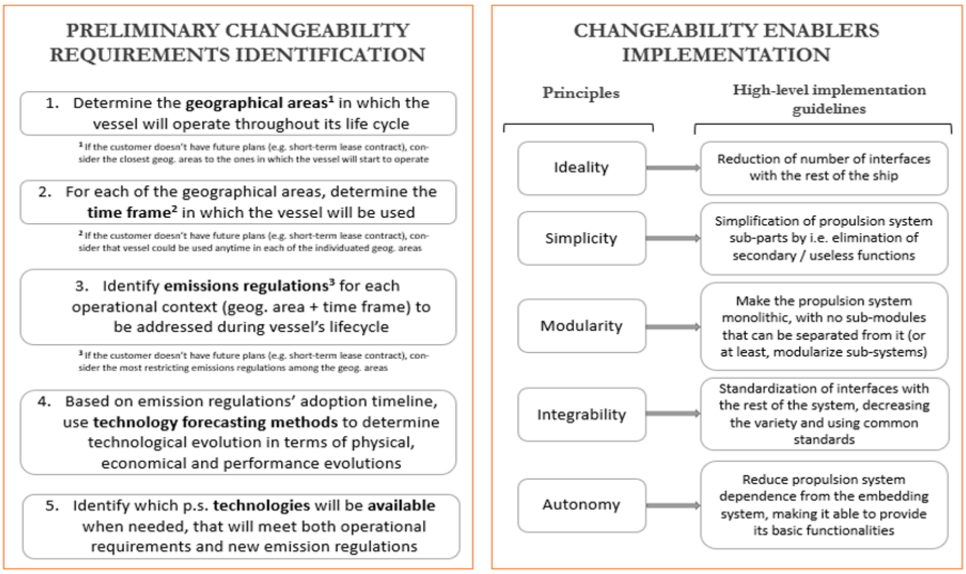

Figure 1 - An approach for maritime propulsion system changeability

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As illustrated in Figure 1, the main principle behind the application of design thinking is to provide a deep understanding of customer needs, and support in the definition of system requirements. As such it was determined that this approach could provide a greater level of collaboration and interaction between stakeholders, improve the quality of the requirements, support in establishing relevant design margins, and prevent the loss of precious information about future vessel operational contexts. A list of preliminary steps to be implemented by designers/engineers from the start of conceptual design phase was developed (Figure 1):

1. Determine the geographical areas in which the vessel will operate throughout its life cycle: this step is fundamental not only because of possible variations of technical requirements, but also because of changing emission regulations based on the geographical area. By ignoring this aspect the company would take a huge risk, since the vessel could potentially not be compliant with local emissions regulations and not be able to operate in it. Whenever it is not possible to access this information for the vessel, assumptions should be made during the design phase (i.e. consider geographical areas close to the one of initial operations).
2. For each of the geographical areas, determine a time frame in which the vessel will be used: since emission regulations change not only based on the geographical area, but especially throughout the time, this step is particularly important to avoid the abovementioned risks. Whenever this information won't be fully accessible for ship-builders, assumptions will have to be made (i.e. it can be assumed that the ship will operate for its whole lifecycle in the nearby of where it starts to operate, that is to say in adjacent geographical areas).
3. Identify emissions regulations for each operational context (geographical area + related time frame) to be addressed during vessel's lifecycle: this step will be a huge advantage if well applied since the risk of not being able to operate because of not being compliant with regulations will be eliminated, except if customer will make different choices of where to operate in the future. Communicating with the customer which regulations he will have to be compliant with will make him more conscious about his hidden needs, that most of the times he wouldn't even be aware of, and this is exactly one of the most important principles in design thinking applications.
4. Based on emission regulations' adoption timeline, technology forecasting methods to determine technological evolution in terms of physical, economical and performance evolutions: this step starts from the abovementioned timeline of regulations, which serves as an input to the use of forecasting methods to determine propulsion systems evolution within these "deadlines". The type of evolution to be evaluated is in terms of performances, physical size and costs. To gather all this information, is likely that a combination of forecasting method will have to be used among the most common ones: Delphi method, forecasting by analogy, growth curves method and extrapolation. Among them, the Delphi method is probably the most suggested to gather information about economical and physical sizes of technologies. However, the aim of this step is not to suggest the best forecasting method to be adopted, even because it depends on the actor that is going to use them. But since from interviews it was found out that forecasting methods are rarely used for ship design, it is yet a great step to start including them.
5. Identify propulsion system technologies that meet operational requirements and new emission regulations: the term "available" refers either to the adoption on a large scale of the specific technology in the market, or at least its introduction in it. The important aspects here that need to be evaluated are the ability of the technology to meet operational requirements (so efficiency, power, speed etc.) and emissions regulations. Once this has been performed this data will be an input for finalizing the concept design phase. In the latter in stages more reliable estimations are done in terms of system characteristics, and that will bring to evaluate in monetary terms which of the future propulsion systems will better perform. Thus, a small set of the best alternatives will be considered while designing the ship for propulsion system changeability.

To simplify the framework, the individuated principles have not been prioritized, given their similar overall impact on changeability implementation. The way in which they have been described was an outcome of both literature and focus groups research, which allowed to individuate high-level implementation guidelines. As above-mentioned, these guidelines already resulted in the questionnaires provided to the focus groups, but feedbacks received from respondents lead to slightly change some of them to avoid possible misunderstandings and be more effective.

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4.2 Conceptual framework validation and refinement

To provide heightened relevance to the conceptual framework, the framework was validated through a series of interviews with six maritime experts (not involved in the initial focus group) with backgrounds in vessel design (concept, basic and detailed), and ship building that could provide effective feedbacks and suggestions on how to improve the framework and verify its conformity to regulatory future plans. The individuals interviewed were selected due to their international ship-building background, involvement in maritime regulation and familiarity with trends in maritime propulsion development. Interviews were performed through private video calls, divided in two sections: the first one briefly explained research context, state of art and research goals, while the second one was the presentation and discussion of conceptual framework.

- The first part of the framework was approved by the respondents, which underlined the importance of implementing design thinking principles through these preliminary guidelines to catch the hidden needs of the customer. Respondents from the regulatory field agreed as well in this topic, evidencing how this was one of the aims of regulations when they have been developed.
- The second part of the framework, even if all the respondents agreed in the paramount importance of changeability enablers, they all underlined the need for a methodological step that, during the preliminary design phase, would provide the possibility for quantifying changeability (if possible in terms of cost, time, and design margin optimality. This was the most important feedback that emerged during the validation process, and it deserved to be better discussed during the framework refinement.

Within the Changeable Maritime Propulsion System Design Framework the definition of a methodology that could quantify changeability level in terms of time and cost had to be considered during the preliminary design phase, since in it some high-level estimations can be performed. Based on the SoA findings a bottom-up approach was identified as being the most suitable, since it begins by considering different design alternatives to estimate cost and time of change for each solution, and then it creates percentage indicators of changeability level (Rehn et al., 2019).

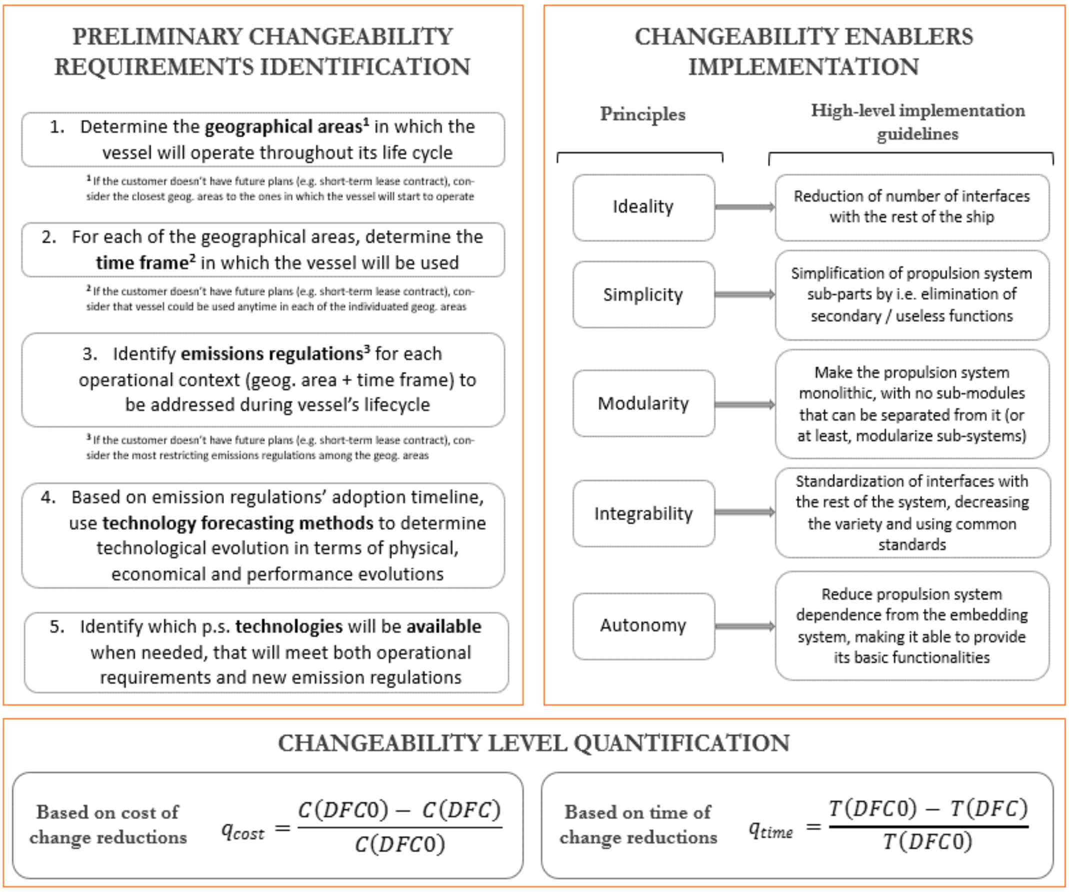

Figure 2 – Conceptual framework (final version)

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As shown in the bottom of Figure 2, Design For Changeability (DFC) refers to the number of path enablers to be implemented in the ship design, which in this case can go from 1 to 5 and for a same value can represent different combinations of them; DFC0 refers instead to the baseline design, without the implementation of changeability enablers. C is a function of DFC variable, indicating the cost of change for a specific design configuration. Therefore, qcost is a ratio, deriving from the difference between cost of change with baseline design and cost of change with a specific changeable design configuration, divided for the cost of change with the baseline design. In other words, it is the changeability metric for the normalized reduced cost from the given change. Its values can go from 0 (changeability level is = 0%) to 1 (changeability level is 100%). The qtime function (Figure 2) is an indicator of changeability level based on time for change estimations. In other words, it is the changeability metric for the normalized reduced time from the given change. T is in fact the time of change for a specific design configuration (DFC). Also, this function can have values from 0 (changeability level is = 0%) to 1 (changeability level is 100%).

4.3 Considerations for adoption

The implementation of the Conceptual Framework wouldn't be possible without strong collaboration between ship-builders and customers. This is the most important challenge maritime industry has to face: as it emerged from the interviews with ship building experts, when making orders for new vessels, customers directly send their technical requirements to the company without the possibility for a more profound collaboration. On one hand, the customer is less conscious about risks they could incur without having a vessel designed for changeability. On the other hand, ship builders won't have a deeper level of customer future needs nor a support in technology forecasting and related changeability design choices. Thus, a minor cultural change is required in order for the value of the framework to be realized during the development process, involving both customers and ship-builders.

5 CONCLUSIONS

This study contributed to develop a conceptual framework that can help maritime engineers and architects designing maritime propulsion systems for changeability. To accomplish this a literature review on changeability, its applications in systems engineering and fundamentals of ship design has originally been conducted, leading to assess literature contribution to these topics. Having defined a gap for what concerns changeability applications to ship design, particularly referring to concrete design frameworks, focus groups research with both design thinking experts and maritime architects and engineers have been conducted. Throughout the aforementioned methodological steps, this study allowed to integrate design thinking, changeability (design margins, coupling, change types, and externalities) and maritime design to generate a framework to help extend the value of maritime vessels. The latter has been lately validated through interviews to a panel of international ship-building and maritime regulations experts, the better way to ensure that this model would be really useful in the real world. Based on resulting feedbacks, the framework has been refined and so the final version of it has been created (Figure 2). In the future, further research should be conducted on these topics:

- Application of presented framework in real case studies: this would allow to better refine its implementation phase and arrange the model according to concrete feedbacks;
- Quantification of changeability level: literature highlighted a lack of methodologies to quantify changeability level, and at the same time the one proposed by this framework doesn't allow to consider all the different aspects related to it. Further research should identify other drivers and other characteristics to be considered in the quantification;
- Changeability Cost: literature highlighted also a lack of methodologies to estimate changeability cost, which is one of the most important parameters to convince customers to implement changeability in their future contracts. Further research should define methodologies to quantify changeability cost.
- Design Margin Optimization for Changeability: while literature exists that enables the design margin optimization for minimizing overdesign/over-engineering, there is limited work into how to calculate, and balance design margins for changeability.

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REFERENCES

Altenhofen JA, Oyama KF, Jacques DR (2015) A methodology to determine the influence of requirements change to support system design. IIE Annu Conf Expo 2015 2181–2190

Beesemyer JC, Ross AM, Rhodes DH (2012) An empirical investigation of system changes to frame links between design decisions and ilities. Procedia Comput Sci 8:31–38. https://doi.org/10.1016/j.procs.2012.01.010

Brahma A, Wynn DC, Isaksson O (2022) Use of Margin to Absorb Variation in Design Specifications: An Analysis Using the Margin Value Method. Proc Des Soc 2:323–332. https://doi.org/10.1017/pds.2022.34

Chhabra JK, Parashar A (2014) Prediction of changeability for object oriented classes and packages by mining change history. Can Conf Electr Comput Eng 1–6. https://doi.org/10.1109/CCECE.2014.6901146

Colombo EF, Cascini G, De Weck OL (2016) Classification of Change-Related Ilities Based on a Literature Review of Engineering Changes. J Integr Des Process Sci 20:1–21. https://doi.org/10.3233/jid-2016-0019

Eckert C, Isaksson O, Earl C (2019) Design margins: a hidden issue in industry. Des Sci 5:1–24. https://doi.org/10.1017/dsj.2019.7

Fricke E, Gebhard B, Negele H, Igenbergs E (2000) Coping with Changes: Causes, Findings and Strategies. Syst Eng 3:169–179. https://doi.org/10.1002/1520-6858(2000)3:4<169::AID-SYS1>3.0.CO;2-W

Gaspar HM, Erikstad SO, Ross AM (2012) Handling temporal complexity in the design of non-transport ships using Epoch-Era Analysis. Trans. R. Inst. Nav. Archit. Part A Int. J. Marit. Eng.

Giffin M, De Weck OL, Bounova G, Keller R, Eckert CM, Clarkson PJ (2009) Change Propagation Analysis in Complex Technical Systems. J Mech Des 131:0810011–08100114. https://doi.org/10.1115/1.3149847

Harvey EJ, Evans J (1959) Basic Design Concepts. J Am Soc Nav Eng 71:671–678. https://doi.org/10.1111/j.1559-3584.1959.tb01836.x

Jarratt TAW, Eckert CM, Caldwell NHM, Clarkson PJ (2011) Engineering change: An overview and perspective on the literature. Res Eng Des 22:103–124. https://doi.org/10.1007/s00163-010-0097-y

Mcmahon CA (1994) Observations on Modes of Incremental Change in Design Design. J Eng Des 5. https://doi.org/10.1080/09544829408907883

McManus H, Richards MG, Ross AM, Hastings DE (2007) A Framework for Incorporating "ilities" in Tradespace Studies. Am Inst Aeronaut Astronaut 1–14. https://doi.org/10.2514/6.2007-6100

Mekdeci B (2013) Managing the impact of change through survivability and pliability to achieve variable systems of systems

Mekdeci B, Ross AM, Rhodes DH, Hastings DE (2015) Pliability and Viable Systems: Maintaining Value under Changing Conditions. IEEE Syst J 9:1173–1184. https://doi.org/10.1109/JSYST.2014.2314316

Misra SC (2015) Design principles of ships and marine structures

Rehn CF, Garcia Agis JJ, Erikstad SO, de Neufville R (2018a) Versatility vs. retrofittability tradeoff in design of non-transport vessels. Ocean Eng.

Rehn CF, Pettersen SS, Erikstad SO, Asbjørnslett BE (2018b) Investigating tradeoffs between performance, cost and flexibility for reconfigurable offshore ships. Ocean Eng.

Rehn CF, Pettersen SS, Garcia JJ, Brett PO, Erikstad SO, Asbjørnslett BE, Ross AM, Rhodes DH (2019) Quantification of changeability level for engineering systems. Syst Eng 22:80–94. https://doi.org/10.1002/sys.21472

Ross AM, Rhodes DH (2008) Using attribute classes to uncover latent value during conceptual systems design. 2008 IEEE Int Syst Conf Proceedings, SysCon 2008 7–14. https://doi.org/10.1109/SYSTEMS.2008.4518981

Sahoo PK (2021) Principles of Marine Vessel Design: Concepts and Design Fundamentals of Sea Going Vessels. World Scientific Publishing

Schulz AP, Fricke E (1999) Incorporating Flexibility, Agility, Robustness, and Adaptability Within the Design of Integrated Systems - Key to Success ? Design 1/17 pp. v:1–8. https://doi.org/10.1109/DASC.1999.863677

Sullivan B, Rossi M, Ramundo L, Terzi S (2019) Characteristics for the implementation of changeability in complex systems. In: XXIII Summer School Francesco Turco 2019. Brescia, Italy, pp 1–7

Sullivan BP, Ansaloni GMM, Bionda A, Rossi M (2022) A life cycle perspective to sustainable hydrogen powered maritime systems - functional and technical requirements. Int J Prod Lifecycle Manag 14:282–301. https://doi.org/10.1504/ijplm.2022.125822

Sullivan BP, Rossi M, Terzi S (2018) A Review of Changeability in Complex Engineering Systems. In: IFAC-PapersOnLine. Elsevier B.V., pp 1567–1572

Uckun S, Mackey R, Do M, Zhou R, Huang E, Shah JJ (2014) Measures of product design adaptability for changing requirements. Artif Intell Eng Des Anal Manuf AIEDAM 28:353–368. https://doi.org/10.1017/S0890060414000523

Universtiy A (2016) Shipyard engineering Lecture 2-1: Design processes and systems

Valerdi R, Sullivan BP (2020) Chapter 3 - Engineering systems integration, testing and validation. In: Handbook of Engineering Systems Design. Springer, p 27

Vossen C, Kleppe R, Randi S (2013) Ship Design and System Integration. In: DMK 2013