☒ Oral Presenter

A Conceptual Framework for Maritime Propulsion Systems Changeability

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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 CO_2 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 design ships for propulsion system changeability, which integrates contributions from literature review with the knowledge of design thinking experts and precious insights of maritime industry professionals. It consists of a set of enablers with related high-level implementation guidelines to be applied during vessel concept development phase, plus preliminary steps to effectively incorporate design thinking principles. The ultimate aim of this framework is defining active ways to increase vessels' value robustness, while improving system's efficiency over time.

Keywords: ***changeability; ship design; design thinking; systems engineering; design for changeability; ilities; conceptual design; value robustness; emission regulations.***

1. Introduction

The maritime industry is and has historically been a critical factor both socially and economically. When designing maritime vessels, it is important to understand how the system can change to improve efficiency and deliver extended value for the stakeholders. Since change is inevitable, due to shifts in stakeholder preferences and missions or environments, the perception of a systems' value will continually change throughout its lifecycle (Beesemyer, Ross, & Rhodes, 2012). This includes the incorporation and anticipation of integrating new technologies into the engineering and design practices so that vessels can change to provide and deliver critical functions while improving efficiency and reducing emissions over time.

Changeability seeks to provide value irrespective of changes to system context, in order for the system to transition from different states irrespective of time (Mekdeci, Ross, Rhodes, & Hastings, 2015). Also, changeability is a valid alternative to effectively implement the official IMO strategy for new ships, which aims at increasing the energy efficiency not only during the development phase, but also over time, by stimulating innovation and continuous development of technical elements (IMO, 2018). In this way, ship builders will need to develop "changeable" vessels, especially in terms of propulsion systems, which are directly responsible for air pollution. In other words, there is a need to develop vessels that would be able to be upgraded with new propulsion systems during their lifecycle, in order to increase their efficiency not only to be compliant with emissions regulations, but also to try to reduce operational costs. This is exactly what motivated authors to conduct this research, trying to individuate a design framework that could enable propulsion system changeability. 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 phases and eventual upgrade of maritime systems. 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 a proposed framework for propulsion system changeability. Through the incorporation of changeability, vessel usage

information and component attributes can be considered from project conception through system deployment and retrofit. Thus, allowing for marine vessel to adapt to needs and requirements placed upon them.
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 be incorporated at a future time. 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 and changeability into propulsion system design. This paper introduces of a group of enablers and guidelines to be implemented during the concept development phase, that can positively increase and extend the lifecycle value of maritime vessels.

1.1 Motivations

Change, in all its forms, is becoming nowadays one of the most relevant factors in every field. This is particularly true when referring to vessels: as complex engineering systems, change is impacting them not only during the development phase but also throughout their overall lifecycle. Maritime industry is currently undergoing significant changes, which derive from the combination of relevant changes in external factors. It is possible to identify three main external factors having the highest impact, that correspond to the study motivations and can be synthetized as follows:

- **Change in Maritime Emissions Regulations**: International Maritime Organization has developed future plans for reducing pollutants emissions from ships. They particularly focused on Greenhouses Gas emissions –the ones impacting climate change– of ships of more than 400 Gross Tonnage (GT), with the goal of reducing CO_2 emissions from international shipping by at least 40% by 2030, compared to 2008 levels (IMO, 2018).
- **Changes in vessels lifecycle**: progressive reduction of vessels life expectancy: while the average lifetime of a modern vessel used to be between 25 and 30 years, in the very last years this is decreasing towards 20 years (Bloomberg, 2016). The underlining reason relies in a constant decrease of vessels value, as the secondhand ship prices reached their lowest value since 2000 (Banchero Costa, 2017; Clarksons Research, 2016).
- **Changing in market dynamics**: maritime industry is undergoing a huge consolidation, with the top five companies' market share in 2018 accounting to a projected 57%, and eight of the top twenty players being eliminated from the industry within in the last two years (Halff et al., 2019). Combining these data with the increase of year-to-year revenues –equal to +18.26% in marine transportation in 2018– and net margins (CSImarket, 2018), competition in this market is growing as well. This indirectly implies that companies will try to reduce operational costs even more, pushing ship builders to develop vessels with a higher efficiency throughout the entire lifecycle.

2. Methodology

A two-steps methodology has been adopted to conduct research for this study, consisting in literature review and focus groups research. In order to individuate the State Of Art (SOA) for changeability in systems engineering, literature review has been performed through the most important online databases. Thus, based on SOA findings, focus groups research has been conducted to gather all relevant knowledge to formulate the conceptual framework.

2.1 Literature Review

In order to analyze literature contribution in terms of changeability in systems engineering, two main databases of abstract and citation database of peer-reviewed literature have been chosen: Scopus and Google Scholar. Papers have been first filtered based on their field (Engineering), document type (paper & article) and language (English). Subsequent filtering has been made for keywords, then field of interest exclusion, extensive literature review, with abstract reading being the last filtering step. The resulting 174 documents contributed to define the SOA for changeability in systems engineering. Thus, it has been possible to define the fundamentals of systems engineering. Then, changeability has been defined as an "umbrella term for several change-related ilities" (Edoardo F. Colombo, Cascini, & De Weck, 2016), with four main ilities related to it: flexibility, robustness, adaptability and agility. System externalities have been analyzed as well, being one of the most impacting agents for changeability, consisting in dynamic marketplace, technological evolution, variety of environments and policy externalities [(Schulz & Fricke, 1999); (Sullivan, Rossi, & Terzi, 2018)]. In order to complete the SOA, research in fundamentals of ship design has been performed, highlighting which are the main process steps, main design methodologies -i.e. the ship design spiral by Evans (Evans, 1959)-, main parameters influencing ship energy efficiency and main emission regulations plans.

The SOA underlined that little research has been performed especially in changeability application to vessel design, and more in general in changeability in maritime industry, so the motivations of this research have been definitely confirmed.

2.2 Focus Groups Research

In order to fill the abovementioned gaps found in SOA, Focus Groups research has been chosen as the most suitable methodology: it gives the right mix of creativity and flexibility that is required to gather needed information in this field. In particular, this research has been conducted first with a panel of design thinking experts at Center for Design Research Stanford University, and then with a group of international experts in ship-building. The former contributed firstly to understand how to possibly integrate design thinking principles in ship design process, and then to evaluate which are the possible enablers of propulsion system changeability in vessel design. Then, interviews with maritime experts led to discover insights on the actual ship development process -particularly for aspects related to changeability, current techniques to predict future lifecycle operational contexts, etc.-. Eventually, all of these experts evaluated which are the most impacting propulsion system changeability enablers in ship design. Mixing the new insights and knowledge that arose from these focus groups, it has been possible to determine which are the actual enablers for maritime propulsion systems changeability and discover new possible 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 in order to well explain their importance and impact on conceptual framework.

3.1 Changeability Overview

Changeability consists in a collective term that represents the ability of a system to change form, function, or operation, according to system characteristics and ilities such as flexibility, agility, adaptability, evolvability, upgradeability, and versatility. A change is defined as the transition of a system from state i to a future state at time i+1 (Ross, Rhodes, & Hastings, E, 2007). Changeability is therefore representing the ability for a system to change from one state to another irrespective of the effects of time, in order to provide for active system value (Ross et al., 2007). The definition provided by Ross is suited due to its higher level of assessment and ability to facilitate universality and relevance in the field (Ross, 2006). Derived from technological literature, this definition does not present a distinction for the suitability of change in systems, it rather focuses on the number of acceptable changes that a system can make.

All systems aim to provide some level of value to stakeholders occupying or utilizing that system (Boehm, Koolmanojwong, Lane, & Turner, 2012). Despite the possibility for change to a system propagated by a shift in the system mission or environment, it is within the interest of the stakeholder that the system continues to provide value (Mekdeci, 2013). Change related ilities allow for the realization of systems that maintain to provide value in the presence of change throughout a systems life. This traditionally has been accomplished through the development of robust systems (passive value) that are capable to absorb changes with minimal negative effect to the entire system. Changeability instead allows for dynamic value sustainment, where the incurrence of change in a system extends the value of a system in an active manner.

- Passive value is delivered through the development of designs insulated by system shells, which are perceived to maintain value over time irrespective of change (Ross, Fitzgerald, & Rhodes, 2011), meaning that design alternatives are selected based on their ability to deliver value to stakeholders in spite of changes in needs or context (value robustness).
- Active value generally requires less contextual and operational system knowledge, though does increase the complexity of the decision process by requiring an agent to initiate changes that allow the system to maintain a high value perception throughout its life (Ross & Rhodes, 2008c).

3.1.1 Change Types

All changes can be seen as both threats and opportunities. On one hand, changes enacted by the agent 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, Eckert, Caldwell, & Clarkson, 2011). The forces representing what the system must respond is categorized on how each change emerges depending on the agent and the decision taken (impact, observation, decision-making) (Table 1).

Table 1: Change Types and Change Agent (E. F. Colombo, Cascini, & de Weck, 2016)

Change	**Agent**
Initiated Change	Reason external to the technical system
Emergent change	Reason internal to the technical system
Propagated change	Another change inside the technical system

- **Initiated Change**: Can be planned and unplanned changes that are generated by an outside source. The most typical initiated change is due to change in requirements. Several papers (Altenhofen, Oyama, & Jacques, 2015; Fricke, Gebhard, Negele, & Igenbergs, 2000; Mcmahon, 1994) distinguish the reasons for change into generic and specific to the project; the latter can be separated according to the stakeholders' degree of control.
- **Emergent Change**: Are "caused by the state of the design, where problems occurring across the whole design and throughout the product life cycle can lead to changes" (Ross & Rhodes, 2008b).
- **Propagated Change:** Undesired changes that come due to other changes having been made (Giffin et al., 2009).

3.1.2 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 (de Weck, 2011). Socio variables have been considered as critical impact factors in systems engineering since the 1970's (INCOSE, 2004). 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 (Fricke and Schulz, 2005).

- **Dynamic Marketplace**: 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 (Fricke and Schulz, 2005). Systems must stay ahead of competition (changeable) during design, development and post deployment to satisfy market and customer needs. Can be affected by policy and regulations, while affecting technological evolution and variety of environment.
- **Dynamic Regulations**: represents regulations mandating some aspect of the system (Ross and Rhodes, 2015). Effected by the market though needs, this externality affects technology choice and environment.
- **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) (Schulz, Fricke and Igenbergs, 2000). 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 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).
- **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 and embedded system (SoS) can be impacted by all changes placed upon the system and are affected by the evolution of technology (Ross & Rhodes, 2008a).

3.2 Change Related System Ilities & Principles

"Ilities" are grounded in strategic thinking and decision theory, as both fields encourage the long-term valuation of actions to promote extend value (Ross et al., 2007). Within systems thinking, "ilities" refer to the theoretical and applied notion of change within systems (E. F. Colombo et al., 2016), determining not only what is changing, but also determining how changes are enacted throughout a systems lifecycle, which enables for class distinctions (McManus, Richards, Ross, & Hastings, 2007). "Ilities" provide an applied and theoretical backdrop to manage system development in the consideration of: system roles/expectation, functions, environments and missions, as well as the seminal responsibility for determining the final systems form.

According to the specific research track, there is a large number of publications and varying definitions relating to "ilities," such as adaptability, and flexibility. In avoiding the perplexity of the different fields and their ambiguous definitions, “ilities” are to be understood strictly as “requirements of systems … often ending in the suffix “ility”: properties of systems that are not necessarily part of the fundamental set of functions or constraints and sometimes not in the requirements” (de Weck, 2011). One of the most well-known classifications of change-related ilities is the one by Fricke & Schulz, that identified two sub groups (Fricke & Schulz, 2005). The first group of ilities is related to active ways to achieve value robustness ilities, and consists in:

- **Flexibility**: the ability of a system to be changed easily;
- **Agility:** ability of a system to be changed rapidly.

The second one, related to passive ways to achieve value robustness, consists in:

- **Adaptability**: ability of a system to adapt itself without external actuation;
- **Robustness:** insensitiveness of the system towards changes coming from the environment.

In order to effectively implement these change-related “ilities” in a system, Fricke and Schulz proposed a set of so-called “system principles for changeability”, also known as changeability enablers (Fricke & Schulz, 2005). They typically consist in a specific possible characteristic of the system that can impact one or more “ilities”. They can be divided in two main categories:

- **Basic Principles**: they support all the four “ilities” of changeability, resulting in: Ideality/Simplicity, Independence, Modularity/Encapsulation;
- **Extending principles**: they support only selected “ilities” of changeability, and consist in: Integrability, Autonomy, Scalability, Non-Hierarchical Integration, Decentralization, Redundancy.

3.3 Ship Design Overview

Ship development process is characterized by high complexity throughout its multiple phases. The classification and definition of general ship design phases has been conducted by Ventura (Ventura, 2010) and Aalto University (Aalto Universtiy, 2016), and the resulting general methodology is depicted in *Figure 1*.

Figure 1 - Ship Design Process stages (Aalto Universtiy, 2016)

Concept Design phase is the very first stage of the ship design process, and it 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. The subsequent phase -**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. Furthermore, main hull dimensions are determined, together with some ship form coefficients and other basic parameters. **Basic Design** phase starts a sort of 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. This step finishes with the creation of a production plan. **Detailed Engineering** then starts with the creation of detailed material for hull production, together with material procurement-related activities. Also, support to the assembly is provided and participation to the working activities often happens, in order to make the ship detailed design effective. Eventually, **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 (Aalto Universtiy, 2016).

3.3.1 Ship Design Methodologies

The development of ship design methodologies over the last decades that emerges from literature underlines how much this industry has been stuck to its traditions and reference models. The most significant contribution in fact relies in the

well-known “Ship design spiral” by Evans (Evans, 1959) (*Figure 1*). This methodology 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.
Clearly, the spiral is more suited to the detailed phases of the design process, rather than to the preliminary and 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.

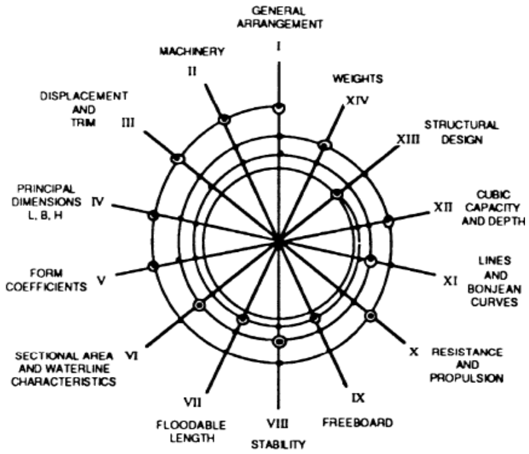

Figure 2 - Design spiral (Evans, 1959)

A real evolution of this methodology came up only in 1981, when Andrews introduced the Creative Ship Design methodology (Andrews, 1981). 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.

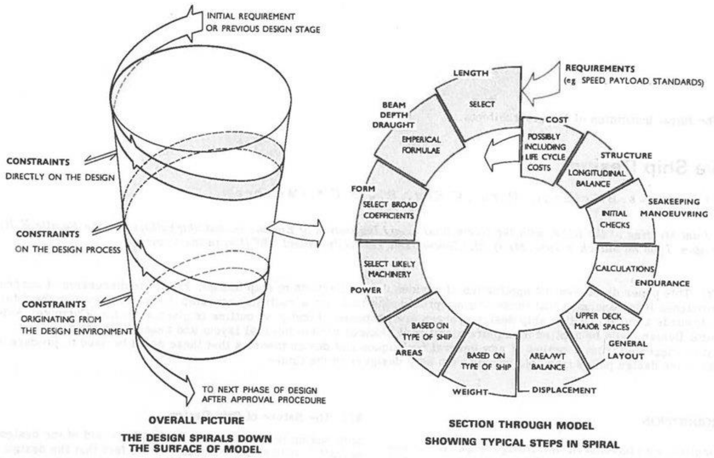

Figure 3 - The Evans-Buxton-Andrews ship design spiral (Andrews, 1981)

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 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.

3.4 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 tradeoff of versatility vs. retrofittability, 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 tradeoffs 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 analyzes the number of configurations that could be changed (upgraded) at a given cost and time (Rehn et al., 2019).
It was found out that a clear conceptual framework with defined elements able to implement changeability in ship design doesn't exist yet, which is another confirmation of the research that has been performed.

4. Design for Changeability Framework

Integrating the knowledge of design thinking experts with the precious insights acquired from ship design experts, and combining them with the findings coming from literature contribution, led to generate a first version of the conceptual framework for maritime propulsion system changeability, which will be better described in the following sub-chapters.

4.1 Framework aims and objective

The purpose of the abovementioned conceptual framework is to provide a concrete approach to help ship builders in designing vessels for propulsion system changeability, in order to effectively overcome current and future challenges in maritime industry. This methodology has also to enable the official strategy by IMO to increase ship energy efficiency over time by stimulating innovation of technical elements. 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 concrete applications.
In particular, the framework should focus on concept design and preliminary design phases, since it was found out both in literature and in interviews that they are the most impacting phases in terms of change. The focus should be on propulsion systems as well, being not only the single "core" design parameter that can be changed over time, but also the most impacting in terms of propulsion systems.

4.2 Conceptual Framework Overview

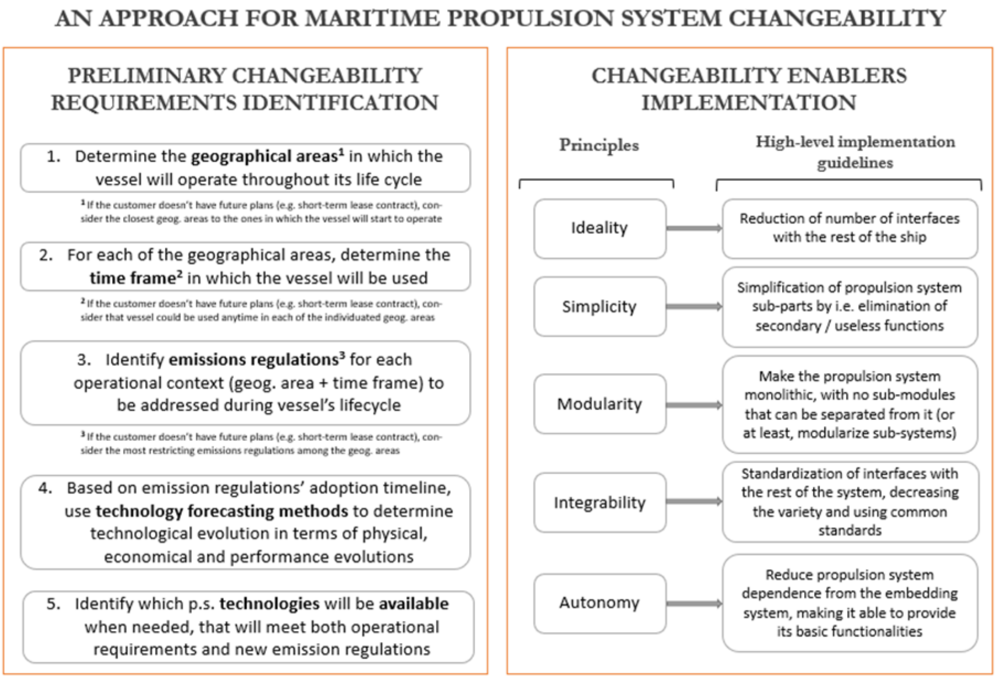

Figure 4 – Conceptual framework (first version)

In an effort to achieve all the aforementioned goals and aims while developping the conceptual framework, the best compromise has been to divide it in two main 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 identifyes which are the high-level implementation guidelines to facilitate the inclusion of maritime propulsion systems changeability principles yet from the concept design phase.
All the knowledge on applications of design thinking methodologies that has been developed at Stanford gave the inspiration to develop the first part of the framework. During the designX sessions at CDR it was found out that the main principle behind the application of design thinking techniques was the deep understanding of customer needs, translating them into detailed requirements. However, ship-builders seem to have lack of consideration for customers deep needs: while contracts are formalized based on technical requirements, a proper collaboration and interaction with the customer is missing at the beginning of most of the projects, causing the loss of precious information about future use of the ship in

terms of operational context. For that reason a list of preliminary steps to be implemented from the start of conceptual design phase has been developed, guarantying to include precious needs that most of the times wouldn't even be well-thought-out. Here is the list, with relative description for each step:

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 wouldn't be possible to access to this information for all the ship lifecycle for whatever reasons, some 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 the **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. Also, directly showing to 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, use **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 which propulsion system technologies will be **available** when needed, that will meet both 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 step has been performed these data will be not only inputs for finishing the concept design phase, but coupled with information emerging from the previous step will also be a fundamental input for the preliminary design phase. In the latter in fact 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. Also, it would be too risky to focus at this stage just on one alternative, cause these calculations are based on forecasts: that's why a -still- limited number of best alternatives should be considered.

The resulting first part, called "*Preliminary changeability requirements identification*", is depicted in *Figure 4* left side.

The second part of the framework originated from the idea of combining both literature and focus groups research contributions into something that could've been integrated in ship development process yet from the conceptual design. During focus groups, respondents had been provided with a questionnaire in which they had to evaluate which of the 9 principles introduced by Fricke and Schulz (Fricke & Schulz, 2005) were the true enablers of maritime propulsion systems changeability. To ease this evaluation, high-level implementation guidelines of these principles in the maritime sector have been provided as well. of them. In both cases, almost 70% of impact contribution was given by only 5 principles out of the 9 considered. Differences in terms of percentages and order of impact of different principles could be noted, motivated by an evident different mindset and background of respondents. In particular, while for designX members the independence principle has a predominant impact to enable changeability, for ship building experts it has a marginal one. Also, while for ship building experts ideality principle is not highly impacting, for design thinking experts

is the second most impacting one. The decision on which principles to be included in the framework was based on both motivations provided by respondents and literature contributions. In particular, the independence principle risked being already implemented with the autonomy one and so to generate confusion, while ideality principle has been proven in other fields of application -as those analyzed at Stanford- one of the most important ones to implement changeability.
To keep the framework not too much complicated, 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.
The resulting second part, called "Changeability enablers implementation", is depicted in *Figure 4* on the right side.
The bottom-line of this part of the framework is that principles of Ideality, simplicity, modularity, integrability and autonomy should be implemented all together during the concept design phase, and that be an input for the subsequent development stages. It doesn't say "how much" of each principle should be implemented, but just gives a high-level implementation guideline for each of them to be incorporated "as much as possible". This will represent an input further development phases, in which i.e. the number of propulsion system's interfaces with the rest of the ship will be optimized based on economic and operational evaluations.

4.3 Conceptual Framework Validation & Refinement

In order to give more relevance to the conceptual framework, a validation process has been performed. The choice has been to conduct interviews with some highly-experienced people that could provide effective feedbacks and suggestions on how to improve the model and verify its conformity to the regulatory future plans. Thus, a panel of international ship-building and maritime regulations experts was selected to properly validate the model. Interviews have been 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 has been generally 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. They also approved the need of a deeper collaboration with the customer in order to really be able to implement changeability. 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.
For the second part of the framework instead, even if all the respondents agreed in the paramount importance of changeability enablers, they all underlined the need for a methodological step that, especially during the preliminary design phase, would give the possibility to quantify changeability in some ways, if possible in terms of cost and time (the ones at which customers pay more attention). This was the most important feedback that emerged during the validation process, and it deserved to be better discussed during the framework refinement.
The definition of a methodology that could quantify changeability level in terms of time and cost had to be particularly referred to the preliminary design phase, since in it some high-level estimations can be performed. In literature, one of the first and most recent methodologies to quantify changeability level has been offered by Rehn (Rehn et al., 2019), divided in two alternative approaches: top-down and bottom-up. The bottom-up approach is the most suitable for this dissertation objectives, since it starts from different design alternatives to estimate cost and time of change for each solution, and then it creates percentage indicators of changeability level. It is presented below a simplified version of their approach, in which q_{cost} is a function of cost of change referring to changeability level:

$$q_{cost} = \frac{C(DFC0) - C(DFC)}{C(DFC0)}$$

Design For Changeability (DFC) variable 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, q_{cost} 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%).

$$q_{time} = \frac{T(DFC0) - T(DFC)}{T(DFC0)}$$

The q_{time} function 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%).
With the incorporation of changeability level quantification, the validation and refinement process of the framework has been completed, and the resulting methodology is depicted in *Figure 5*.

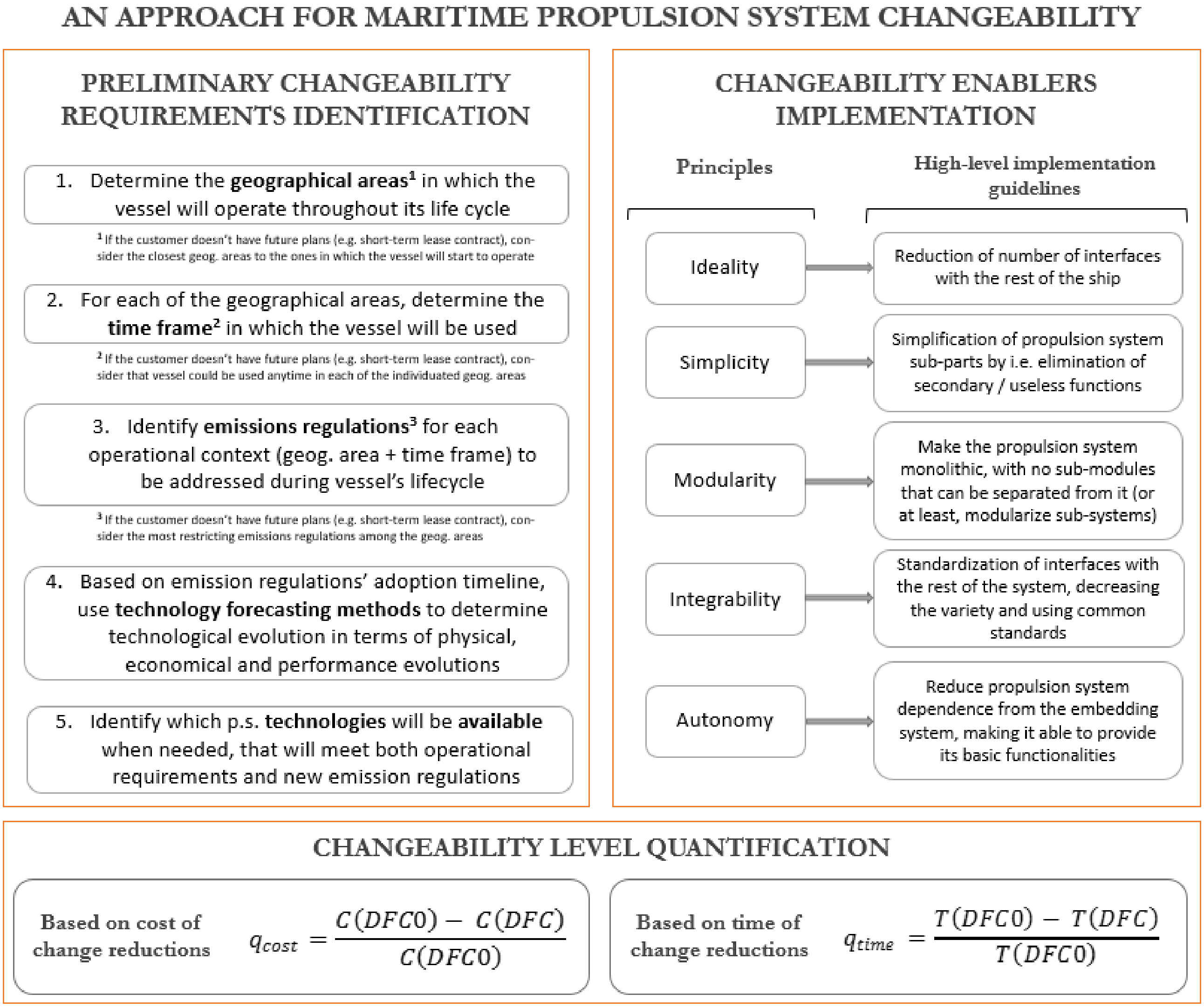

Figure 5 – Conceptual framework (final version)

4.4 Considerations for Adoption

The application of the presented Conceptual Framework wouldn't be possible without an intense collaboration between ship-builders and customers. This is probably 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 giving the possibility for a more profound collaboration. On one hand, in this way the customer is less conscious about risks he could incur without having a vessel designed for changeability -such as impossibility to operate in the future due to emissions rules or high cost of change-. On the other hand, ship builder won't have this deeper level of customer future needs nor a support in technology forecasting and related changeability design choices. Thus, a cultural change is needed to let design thinking principles really impact in the development process, involving both customers and ship-builders.

5. Conclusions and Future Work

This study contributed to develop a one-of-a-kind conceptual framework that will 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 the expertise in design thinking from CDR design thinking experts with the precious insights and knowledge of maritime industry experts, combining them with the state of art findings in order to generate a one-of-a-kind design framework. 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 5*).

In the upcoming 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.

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