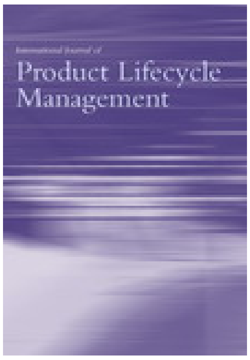

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A life cycle perspective to sustainable hydrogen powered maritime systems – functional and technical requirements

Brendan P. Sullivan, Giuditta Margherita Maria Ansaloni, Arianna Bionda, Monica Rossi

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A life cycle perspective to sustainable hydrogen powered maritime systems – functional and technical requirements

Brendan P. Sullivan*
Department of Management, Economics, and Industrial Engineering,
Politecnico di Milano,
Via Raffaele Lambruschini, 4/B,
20156, Milano MI, Italy
Email: brendan.sullivan@polimi.it
*Corresponding author

Giuditta Margherita Maria Ansaloni and
Arianna Bionda
Department of Design,
Politecnico di Milano,
Via Giovanni Durando, 10,
20158, Milano MI, Italy
Email: giudittamargherita.ansaloni@polimi.it
Email: arianna.bionda@polimi.it

Monica Rossi
Department of Management, Economics, and Industrial Engineering,
Politecnico di Milano,
Via Raffaele Lambruschini, 4/B,
20156, Milano MI, Italy
Email: Monica.rossi@polimi.it

Abstract: The International Maritime Organization has set the goal of reducing CO_2 emissions from international shipping by at least 40% by 2030, compared to 2008. To meet this target, ship builders are evaluating alternative fuel sources capable of increasing energy efficiency. This paper presents technical and functional requirements specific to the operationalised middle of life cycle phase. These requirements have been established from a comprehensive literature review and focus group with maritime vessel designers and engineers.

Keywords: product life cycle management; PLM; sustainable systems; hydrogen; vessel requirements; technical requirements; functional requirements; maritime; vessel design; Sustainable Development Goal; SDG; clean energy; systems engineering.

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Biographical notes: Brendan P. Sullivan received his PhD in Industrial Engineering from Politecnico di Milano (POLIMI), Milano, Italy in 2020. His research focuses on system testing and evaluation, and changeable system architectures.

Giuditta Margherita Maria Ansaloni is a Research Fellow at the Department of Management, Economics and Industrial Engineering at Politecnico di Milano.

Arianna Bionda is an Assistant Professor at the School of Design at the Politecnico di Milano, and Scientific Coordinator of the Master in Yacht Design. Her research activities focus on innovative technologies and materials for yacht design.

Monica Rossi is an Assistant Professor at Politecnico di Milano University, Department of Management, Economics and Industrial Engineering and faculty member of the School of Management at Politecnico di Milano (MIP). Her research focuses on lean product and process development, lifecycle thinking, and product lifecycle management.

1 Introduction

The maritime industry is and has historically been a critical factor for both social and economic growth. However increased shipping demands, and extended vessel life cycles threaten to increase the roughly 2%–3% of global greenhouse gas (GHG) emissions currently generated and could grow by up to 50% by 2050 (Erbach, 2020).

In the last decade, environmental sustainability has become a primary policy concern in the evolution of transport sector for goods and people, sustainable transport, and sustainable development (UN Sustainable Transport, 2021). In the maritime sector, low carbon shipping and air pollution control is considered a priority (Olmer et al., 2017): the emissions from ships exhausts into the atmosphere and the seawater are harmful for the marine ecosystem as well for the human health, increasing the acid rain effect and contributing to global warming (Eyring et al., 2015). The International Maritime Organization (IMO) and GHG study forecasted a growth in CO_2 emissions for international maritime transport of 50 to 250% in the period up to 2050. Although international shipping is already the most energy-efficient mode of mass cargo transportation (Wang, 2013), a global approach to further enhance energy efficiency and effective emission control is needed as demand increases (IMO, 2022a). Furthermore, in the recent years the maritime sector and the passenger transport industry have started several initiatives in line with the global social and environmental challenges, the 2030 and 2050 UN sustainability agendas and its 17 Sustainable Development Goals (SDGs) (DESA, 2022). Environmentally driven regulations are increasingly affecting waterborne transport market dynamics, targeting a clean fuel economy and its sustainability (Al-Enazi et al., 2021). Given the fleet growth up and the needs for marine transportation of goods worldwide, the reduction of CO_2 emissions demands novel energy efficient technologies (Xing et al., 2022), including transitional such as liquefied natural gas (LNG) (Al-Enazi et al., 2021).

With the aim of tackling this challenge, starting from 2018 IMO has been experimenting an initial strategy on reduction of GHG emissions from ships by setting out a twofold approach: a regulatory work framework building, and a zero carbon fuels market boost supported by capacity building initiatives (IMO, 2022b). Considering future low carbon and zero-carbon fuels for shipping have diverse production pathways (for example, different generations of biofuels, hydrogen-based fuels, etc.) (Bilgili, 2021). Within them, hydrogen-based fuel (H2) and fuel cell (FC) technologies can play a significant role in the Europe's new energy system for maritime sector (FCH Joint Undertaking, 2019). However, H2 and FC technologies for maritime sector and vessel design are not covered nor supported by a specific regulatory framework and lack guidelines for how such an ecosystem can be developed (The European Clean Hydrogen Alliance, n.d.).

Based on UN SDGs (in particular the SDG7 'affordable and clean energy', with connections with SDG13 'climate action' and SDG14 'life below water') (DESA, 2022), hydrogen-based fuels have been identified as one approach to reduce harmful gas emissions. Hydrogen has over the past 15-years been increasingly explored for fuel propulsion due to the reduced environmental impact, significantly lower carbon emissions, and greater propulsion system flexibility (Koroneos et al., 2004). While the cost of hydrogen generation continues to decrease, the transition to faces severs challenges in terms of production upscaling and supply logistics. However, like all revolutionary technologies there is a critical need to create an environment where all aspects of hydrogen can be realised. This requires the development of both vessel and bunkering capabilities whereby new and retrofitted vessels will be able to continue and expand operation.

Product life cycle management (PLM) represent the strategic management and articulation of a system or products complete development process concept, to development, and finally the retirement/disposal of the system (Terzi et al., 2010; Garetti and Terzi, 2003). In respect to maritime this comprehensive perspective both the vessel and supporting bunkering in order for valuable, sustainable, and efficient realisation and is ideal for such a challenge. Also, PLM is a valid strategy to effectively manage the different phases of a vessels life, by considering not only the energy efficiency, but also over time, by creating an environment where innovation and continuous development of technical elements can thrive. In this way, ship builders will need to develop 'sustainable' vessels, that can meet current and future needs. In other words, it will be critical to consider not only propulsion, but also the vessel layout, and bunkering support systems. This expanded view of the situation demands the comprehensive evaluation of various stakeholder perspectives from the beginning to end of life of the system to better understand the operational costs, and larger environmental impact (Sassanelli et al., 2018). Despite the growth and shift in trends to develop zero emission hydrogen powered vessels, a challenge remains in how to leverage this information in the most efficient manner during the beginning, middle and end of life of maritime systems.

This has motivated the authors to conduct this research, trying to individuate needs, requirements and specifications that could support the advancement of hydrogen powered vessels. In an effort to facilitate the realisation of hydrogen propulsion and meet the UN SDGs, standards, and lessons learned can enable a comprehensive life cycle perspective. Through the incorporation of PLM, stakeholder perspectives, vessel usage information and bunkering attributes can be considered from project conception through system deployment and retrofit, to retirement. Thus, allowing for maritime vessels reduce their environmental impact and strengthen the value to stakeholders.

The paper is organised as follows, Section 2 introduces the context and research background related to the effort undertaken within the paper. Section 3 presents the applied research methodology used to formulate the proposed technical and functional requirements. Section 4 presents a review of PLM in the maritime industry considering all phases of the life cycle, relevant approaches related to sustainable life cycle activities, and a description of requirements/standards that support the development of sustainable maritime vessels. Section 5 provides an empirical analysis from the outcomes of the international focus group that supported the ultimate formalisation of technical and functional requirements that aim to facilitate the extended life of maritime vessels, with suggestions to be followed within the identified and most impactful areas of the life cycle. Section 6 introduces the formal technical and functional requirements derived from literature and the aforementioned focus group (Section 5). Section 7 discusses the practical findings of the research. Section 8 synthesises and concludes the findings and practical value of the requirements to foster the realisation of sustainable maritime systems.

2 Context and background

The maritime industry is currently undergoing significant changes, which derive from the combination of new technologies and new infrastructure needs. Recent advancements have demonstrated many potential benefits for the use of hydrogen propulsion, including emissions reduction and scalability. Accordingly, there are three main principal factors that correspond to both sustainability and hydrogen as a fuel.

- *Changes in maritime emissions regulations:* The IMO has developed future plans for reducing pollutants emissions from ships (IMO, 2019). They particularly focused on GHG emissions –the ones impacting climate change of ships greater than 400 gross tons, with the goal to reduce CO_2 emissions from international shipping by at least 40% by 2030, compared to 2008 levels (IMO, 2022b).
- *Changes in the vessel life cycle:* The average lifetime of a modern vessel can be between 25 and 30 years, rapid shifts in technology requires the design of new and retrofitting of older vessels to meet sustainability needs (Luglietti et al., 2018; Sullivan et al., 2022). This means that not only are new fuel sources needed, but also that the infrastructure to support them is put in place.
- *Changing 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; Sullivan et al., 2018a; Vakili et al., 2021). Combining this data with the in this market is growing as well. This indirectly implies that companies will try to reduce operational costs even more, and thus sustainable options must exist (Stanić et al., 2018; Dinu and Ilie, 2015).

As complex engineering systems, the adoption and implementation of hydrogen is no simple undertaking and must consider entire life cycle to become a truly viable fuel alternative (Koroneos et al., 2004; Hwang et al., 2020). However, at present H2 remains focused on the research and test environment, due to a lack of regulatory statutes, international standards, and practical solutions. Recognising this there is a critical need for life cycle requirements to be established that are capable of addressing the design, safety, organisation, and operation of vessels.

The objective of this research is to identify and develop technical and functional requirements most impactful to the life of sustainable maritime systems. This intends to support H2 powered vessel development through an eco-life cycle perspective that focuses on the real implications of requirements during the life cycle.

3 Research objective and method

There are many conceptions about maritime vessel sustainability, but not a clearly articulated explanation of what should be considered for H2 propulsion system realisation. By focusing on requirements, a series of considerations can be concluded that shape both stakeholder value, environmental impact, and overall vessel sustainability. This research focuses exclusively on maritime vessels which due to the long design time, high number of interfaces, unpresented design and long-life span are complex systems (Farr, 2012). Relying on established theory, and system life cycle phases, a set of requirements and design considerations relevant to sustainability will be presented.

3.1 Research questions

The central goal of this research was to develop a set of primary requirements that will support the realisation of sustainable maritime vessels. This goal has been addressed through two research questions.

RQ1 What life cycle phase should maritime system sustainability consider?

RQ2 What requirements related to sustainability should be considered and address for hydrogen realisation?

After evaluating the life cycle phases of maritime systems (RQ1), a set of considerations were developed to support the resolution of the second research question (RQ2). Through this it was possible to formulate primary functional and technical requirements areas that aim to support sustainable maritime vessel development.

3.2 Research approach

According to the scope of this research, a two-step methodology was adopted, consisting of a *literature review* and *open discussion with industry experts through a focus group*. In order to individuate the state-of-the-art and practice for maritime vessels, literature was identified from the most relevant online databases and industrial sources. This effort was enhanced through the evaluation of international and professional standards relevant to the field. Based on the findings, a focus group with industrial professionals was conducted to refine and prioritise the knowledge collected and support the research formalisation.

3.2.1 Literature review

Owing to the novelty of the field, there is not a unified set of requirements that can broadly encapsulate the different life cycle areas of H2 maritime vessels. In an attempt to frame the multifaceted contributions in the industry, the role of stakeholders and applicable requirements were identified as being essential.

Following a controlled approach, as opposed to an intuitive search each step of the review served as a means of identifying the most relevant and impactful literature.

The steps undertaken in this review relied on three central databases: Scopus, Google Scholar, and the International Organization for Standardization (ISO) (Table 1). Publications were then filtered according to research field (Engineering), document type (paper and article) and language (English). Subsequent filtering was performed according to keywords, then field of interest exclusion.

The documents were evaluated based on their abstracts, with low/irrelevant documents being removed. High value publications served as motivational papers for additional review (snowballing), whereby secondary references were evaluated and incorporated into the review. The most relevant documents were used define the state of art for PLM in the maritime industry and identify relevant requirements.

a Hydrogen maritime life cycle publications:
  - Scopus – 17 academic publications (journal and conference).
  - Google Scholar – 24 academic publications (journal and conference).
  - International Organization for Standardization – 11 publications (reports and technical documents).

b Sustainable vessel life cycle requirements:
  - Scopus – 7 academic publications (journal and conference).
  - Google Scholar – 29 academic publications (journal and conference).
  - International Organization for Standardization – 81 publications (reports, technical documents and international standards).

While the number of total academic publications were limited in contrast to those related to international standards, the inclusion of academic works allowed for the categorisation and clustering of the requirements.

Table 1 Literature review search criteria

Keywords	*Criteria*
Maritime life cycle management; PLM; sustainable systems; hydrogen; vessel requirements; technical requirements; functional requirements; maritime; vessel design; sustainable development goal; clean energy; maritime systems engineering	*Inclusion:* English, journal, conference proceeding, and standards *Exclusion:* automation, logistics, security, and radar

3.2.2 Focus group

To have a well-founded basis for this research, a focus group was organised with industry experts involved in the design, development, maintenance, and operation of maritime vessels. The purpose of the focus group was to understand maritime vessel life cycle environmental impacts and value of requirements in the realisation of such systems. The focus group was applied to this research due to the ability to consolidate expert experience involved in hydrogen, maritime engineering, and environmental impact. The outcomes allowed for new sustainability consideration for hydrogen power vessels to be developed that complement existing research in the field and create a comprehensive overview of the requirements and considerations that impact the various maritime life cycle phases.

This research was conducted with project members involved in the eShyIPS EU project, and international experts. Snowball sampling was utilised to identify people who could provide rich information and were otherwise not easily accessible (Naderifar et al., 2017). This method was appropriate for selecting participants due to the specificity of vessel industry and the hydrogen industry.

Table 2 Focus group member composition

ID	*Country*	*Experience*	*Domain*
1	USA	Renewable fuels and energy storage	Research centre – H2 basic and applied research
2	USA	Specialist, zero emission heavy duty vehicles	Zero emission terrestrial transportation
3	France	Product strategy manager	Maritime industrial company
4	Norway	Sales manager	Hydrogen industrial company
5	Spain	Mechanical engineer, R&D department	Maritime industrial company
6	Spain	Head of engineering	Maritime industrial company
7	Sweden	Head of cryogenic LNG development	Maritime industrial company
8	Italy	Project manager in innovation	Research centre and H2 technologies
9	Germany	Product manager	H2 storage and handling
10	Norway	Senior research engineer	International registrar
11	Finland	R&D project manager	Expert in the production/handling/ transport/bunkering of hydrogen
12	Finland	R&D	Technical research centre
13	Germany	Hydrogen stack development	Hydrogen technology provider
14	Netherlands	R&D project manager	Shipbuilder
15	Greece	Product manager	ship operator
16	Cyprus	Naval architect and marine engineer	Ship operator

The typology of the focus group was organised with the authors of this paper as the moderators, where prior to formal interaction a description of the research objectives was presented to establish a list of characteristics for maritime vessel sustainability. The focus groups creation, organisation and process utilised the following steps:

- Establishment of focus group objectives: identify life cycle phases and system requirements related to sustainability.

- Designate number of focus groups to run whereby it was determined that the broad experiences and domains allowed for a single focus group.
- Identify participants: Participants had a minimum of five years' experience, with each being familiar with hydrogen propulsion or maritime vessel design.

The focus group was designed to contribute to the improved understanding of how to integrate life cycle principles in maritime according to firsthand insights from actual sustainable vessel development processes. The individuals identified and selected provided a well distributed group that represent the near-entire life cycle of maritime vessels and provided a mix of creativity and flexibility (Table 2).

The focus group allowed for the discovery of insights on the greater industry, and life cycle considerations for hydrogen, particularly for aspects related to PLM. The outcomes allowed for a preliminary set of technical and functional requirement considerations to be developed according to industry needs and sustainable life cycle principles. The insights and knowledge that arose from these interviews was clustered to determine in which life cycle phases the greatest value can be and discover new possible ways to implement PLM in different contexts.

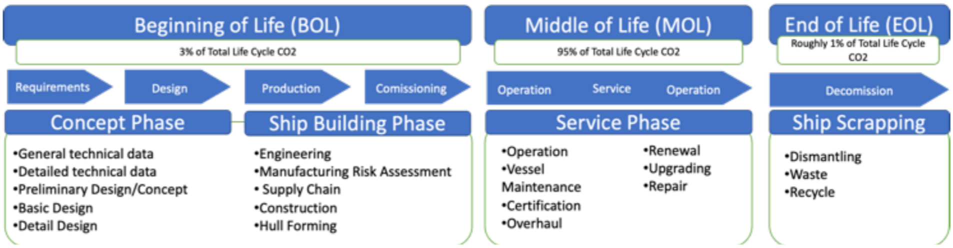
4 State-of-the-art and practice

The most relevant aspects resulting from the state of art and practice have been synthesised in Section 4 and reflect on the roll life cycle of maritime vessels, stakeholder value and vessel requirements. These concepts will be presented in the following subsections to explain their importance and facilitate the rationale for the requirements presented.

4.1 Maritime vessel life cycle

As complex engineering systems with long life cycles the phases and implications of hydrogen powered vessels are highly specific. As a unique and highly technical domain design constraints and requirements are vital to system realisation. In particular, requirements must consider the comprehensive life of the vessel and be compatible with the operational scenario. This considers the hull, machinery, propulsion, piping, fuel storage, and refuelling (Luglietti et al., 2018).

Figure 1 Maritime vessel life cycle (see online version for colours)

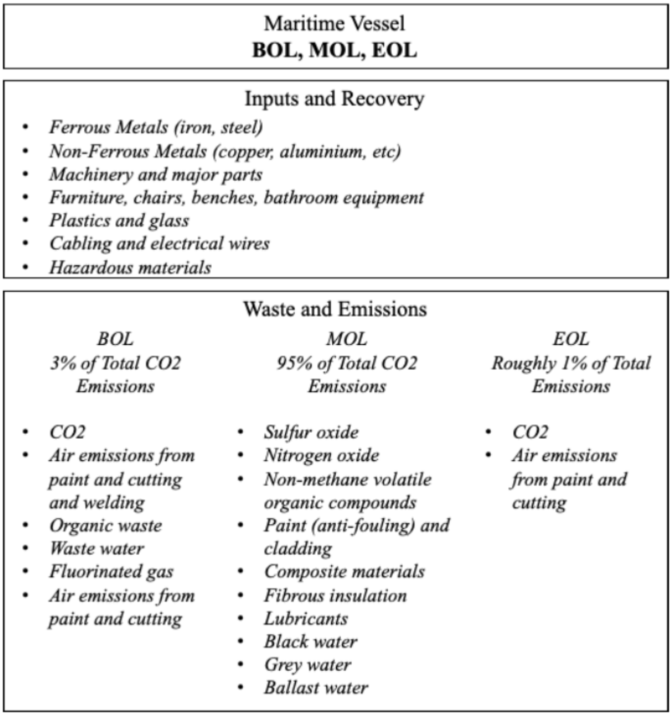


Beginning-of-life (BOL) includes in practice the design and manufacturing of a system or product (Terzi et al., 2010; Montwiłł et al., 2018). While multiple perspectives exist, BOL can be synthesised to represent the recursive implementation of activities that enable the eventual utilisation of a system/product. During this phase of maritime vessel development, use cases, trade studies, requirements analysis and other activities are undertaken to satisfy stakeholder needs. While such activities directly impact the quality, performance, and value a system will ultimately have, the effective operations where the greatest ecological effect is seen cannot be fully realised.

Middle-of-life (MOL) includes the deployment, utilisation, and maintenance of the system (Terzi et al., 2010; Montwiłł et al., 2018). Due to active utilisation, work performed during the BOL is realised and the true life of the system is underway. In the MOL phase the logistics, emissions, operations, harbouring, and bunkering that facilitate the operation can be evaluated, retrofitted, or left alone.

End of life: the vessel is retired and undergoes ship breaking (Terzi et al., 2010; Montwiłł et al., 2018). In order for the vessel to be effectively recycled (disassembled, remanufactured, reused, etc.) the most valuable parts and materials (ferrous/non-ferrous metals) from the ship are recovered. While the circularity of the industry has increased and there has shown a greater resolve to reuse components the improved efficiency offered by hydrogen has the potential to reduce the number of vessels being broken down annually. While ferrous and nonferrous materials are the costliest and most widely reused aspects from vessels shifts towards composite hulls for small and medium sized vessels is another aspect for consideration.

Figure 2 Emissions and material relationships throughout a vessels life cycle



Maritime Vessel
BOL, MOL, EOL

Inputs and Recovery

- *Ferrous Metals (iron, steel)*
- *Non-Ferrous Metals (copper, aluminium, etc)*
- *Machinery and major parts*
- *Furniture, chairs, benches, bathroom equipment*
- *Plastics and glass*
- *Cabling and electrical wires*
- *Hazardous materials*

Waste and Emissions

BOL *3% of Total CO2 Emissions*	*MOL* *95% of Total CO2 Emissions*	*EOL* *Roughly 1% of Total Emissions*
• *CO2* • *Air emissions from paint and cutting and welding* • *Organic waste* • *Waste water* • *Fluorinated gas* • *Air emissions from paint and cutting*	• *Sulfur oxide* • *Nitrogen oxide* • *Non-methane volatile organic compounds* • *Paint (anti-fouling) and cladding* • *Composite materials* • *Fibrous insulation* • *Lubricants* • *Black water* • *Grey water* • *Ballast water*	• *CO2* • *Air emissions from paint and cutting*

As shown in Figure 2, the emissions and wastes for each life cycle phase are synthesised (BOL, MOL and EOL) (Vakili et al., 2021; Gratsos et al., 2010; Ramirez-Peña et al., 2020).

As shown in Figure 2, the BOL and EOL phases have a relatively low environmental impact despite fuel production to power construction, and material processing activities for construction or deconstruction. High emissions and environmental waste produced during the MOL of the vessel greatly contribute to the propulsion system fuel choice, and is through hydrogen expected to radically decrease (Hwang et al., 2020).

4.2 Maritime life cycle value considerations

The desire for valuable maritime vessels, is related to the recognition that stakeholders perception of value will change throughout the vessels life (Sullivan et al., 2020; Keane et al., 2015). Inevitably the effect of time on vessel performance, operating cost, and environmental restrictions represents a persistent series of changes, both for the system and its provided value. Implicitly, value therefore is a key consideration when considering the life cycle of a maritime vessel. Recognising the need to preserve the value of vessels through the implementation of renewable fuels seeks to enhance/sustain/maintain the value of a system throughout its life cycle by either increasing the systems extended technical performance or by reducing the cost of recursive changes that diminish the vessels value. This dictates the management of dealing with mismatches between the vessels design and various stakeholder expectations, including responses to regulations, fuel shortages, or other matters.

Recognising that the industry and society at large are requiring smarter, more efficient, and more sustainable solutions, stakeholders have a more vital role in the BOL, shaping the future of maritime vessels than ever before. Accordingly, a set of critical elements were identified as being highly impactful for sustainability efforts:

- Advances in technology: Technologies such as hydrogen propulsion require new infrastructures new materials, components, techniques, or processes (advances in the state-of-the-art) that are not currently in existence/operation (Luglietti et al., 2018).
- Specifications can become incompatible: User's specifications can become outdated or incompatible with international guidelines (Sullivan et al., 2018b). This can be seen in vessels propulsion demands, which when initially established reflected a low cost of operation and a desire for greater speed.
- Additional design effort is needed: Application of additional skills, ideas, and information need to be considered to evaluate and plan for the sustainable operation of a hydrogen vessels (Sassanelli et al., 2018).
- Design deficiencies can exist: Prior designs can prove inadequate due to the shift in fuel source. This can impact the centre of gravity, bouncy and suitability of the vessel to operate in certain sea conditions (Ricci et al., 2013).

However, as vessels life are being extended it is critical to understand how stakeholder value shifts across life cycle phases. In this respect, focus on the extended value (MOL) of the vessel the following considerations are critical:

- Advances in technology: Similar to the BOL hydrogen propulsion in particular requires the potential for propulsion system retrofit and vessel operational profiles (Luglietti et al., 2018).
- Costs grow: Vessel cost is heavily distributed during the operations phase, due to fuel, crew, port and maintenance costs (Dinu and Ilie, 2015).
- User's change their needs during operation: User's modify or redefine the vessels mission, function and environment due to new environmental restrictions and technologies (Sullivan et al., 2020; Ricci et al., 2013).
- Feedback from test/use can be leveraged: Vessel planning, retrofitting and development is based on experience that can only be gathered through the successful deployment of hydrogen systems (Abramovici and Schulte, 2007).

According to the extended life of maritime vessels the EOL remains a critical point. This can in part be attributed to the current novelty/newness of many propulsion technologies and the implications realised during change and retrofit activities, requesting consideration of:

- System changeability: Decisions made early in the design process (BOL) has a direct impact on the life span and value of the vessel. This is critical as vessel designs today are capable of lasting beyond their expected lives due to the ease of upgrading.
- Material reclamation: Impacted by BOL decisions, materials used during construction and retrofit impact the raw percentage of materials that can be recovered.
- Recovery environmental expense: The process of material recovery and vessel decomposing is one of the lower area of direct environment impact. While a true contributor to greenhouse emissions, the material recovery offset (see point above) on large steel vessels directly offsets.

4.3 Requirements

A requirement represents a formal statement that describes the systems mission, environment, functions, or design characteristics to enable the eventual realisation of the entity (INCOSE, 2011). The requirements process is based on the identification and synthesis of the functions required for any solution associated with performance and other quality measures that will provide the basis for the assessment/testing of solutions and verification of the completed system (INCOSE, 2011; Walden and Roedler, 2015; US Department of Defense Systems Management College, 2001; NASA, 2007).

A performance-based standards (PBS) serves as a product boundary, comprised of a complete set of system requirements including those that are decomposed and allocated down to the design elements. Requirements allocated to the PBS can be functional requirements (what functions need to be performed), performance requirements (how well these functions should be performed), and interface requirements (product to product interaction requirements). Crosscutting requirements include environmental, safety, human factors, and those that originate from the 'ilities' standards (NASA, 2007; Sullivan et al., 2018c). With an understanding of the constrains, physical/functional interfaces, and functional/behavioural expectations, requirements can be further defined by establishing performance and other technical criteria to support the entire life cycle (Sullivan et al., 2018c; Sassanelli et al., 2016).

Functional requirements describe qualitatively the system functions or tasks to be performed in operations. Basic vessel behaviour: including capabilities for responding to users/market needs and demands (Walden and Roedler, 2015; NASA, 2007). Once the functional requirements are fixed, corresponding technical requirements should be identified and established. Technical requirements subsequently specify parameters determine how distinct system needs should be fulfilled/satisfied, in a traceable and prioritised manner.

Following the definition of the aforementioned system requirements, it is important to understand which of these are relevant and which are not. To be able to do so, the needs must be clarified according to the reference system (which is vessels), then both functional and technical requirements can be listed. It must be taken into account that starting from the same functional requirements, different technical requirements can be considered, and different solutions to reach the project objective can be found. The designers should choose which will be aligned and implemented according to the projects general purpose, which in this study focuses on the adoption of a zero-GHG propulsion system for maritime.

While most requirements and specifications involved in vessel design have already been studied and developed, a suitable set of requirements and a normative framework for the implementation of hydrogen-based fuel systems is yet to be developed. The current state of the art outlines that there is no common approach yet to hydrogen fuelled ship requirements (FCH Joint Undertaking, 2019).

The available requirements and specifications that can be applied to vessel design are developed by the IMO: the International Code of Safety for Ship using Gases or other Low-Flashpoint Fuels (IGF Code) is the mandatory IMO instrument that applies to all gaseous and other low-flashpoint fuels in shipping, and to all gas-powered ships other than gas carriers. It contains requirements and mandatory provisions for the arrangement, installation, control and monitoring of the machinery, equipment and system using lowflashpoint fuels: for the time being, ships installing fuel systems designed to operate on other type of low-flashpoint fuels need to demonstrate individually that design meets the IGF Code's general requirements.

5 Empirical analysis

The focus group allowed for the exploration of the current life cycle environmental factors related to the research questions. At the conclusion of the focus group, notes and other observations were reviewed. The discussions were analysed by performing a thematic analysis, in order to organise and report the critical findings related to maritime vessel requirements and sustainability. This thematic analysis followed the essentialist/realist method, which reflects and allows the participants to articulate their meanings and experiences. Thematic analysis is process of identifying patterns or themes within qualitative data (Braun and Clarke, 2006). The results compiled were analysed and compared against the referenced life cycle phases and requirements identified to establish if there were similarities or differences. An advantage, of applying this analysis was that it is very flexible and serves well to synthesise research and establish classes that can be used to categorise the requirements and life cycle consideration necessary for this research.

The results from the thematic analysis presented in this paper illustrate the primary themes within two research areas (sustainable maritime vessel PLM and requirements), as well as a cohesive presentation generated from the two. The themes, codes and their respective definitions can be seen in Table 3.

Table 3 Focus group themes and codes

Themes and codes
'Vessel'
• Vessel focused: Aspects necessary how the maritime vessel should behave or operate. • System focused: Aspects dictating or specifying what the system should be capable of doing throughout its life cycle.
'Life cycle'
• Beginning-of-life: Considers the design and development activities employed to support the creation of the maritime vessel. This includes considerations of international standards, environmental conditions, and technology feasibility studies, amongst other activities. • Middle-of-life: The systems degree of excellence is put under evaluation during the utilisation of the vessel. The performance and evaluation of the vessel under daily operating conditions is brought forth, whereby the real emissions, refuelling, harbouring, and user effects are evaluated. • End-of-life: Upon the diminishment or complete loss of value (as determined by the stakeholder) the system is removed from operation. The sustainability of the vessels design is formally measured through the material recovery, time, energy, and cost to dismantle/recycle/dispose of vessel components.
'Requirements'
• Environmental requirements: Represent and account for all conditions to be encountered or endured by the vessel as it performs and operates according to the operational profile of the vessel. • Operational and logistical requirements: Refer to and relate to the operational conditions or physical properties/components that are required for the vessel to operate or exist in its environment. • Safety requirements: Consider hazards associated with physical layout, operation and maintenance following any reasonably foreseeable failure. • Fuel transport requirements: Refer to and include any method to support the transfer of fuel to the bunkering system, whereby the vessel can then be supplied from. • Fuel storage requirements: Specify how the fuel will be stored for bunkering and is determined by the demand, and vessel scenario requirements. • Infrastructure requirements: Relate to the physical infrastructure that the bunkering system must have to be ensured to guarantee safety, operational efficiency, and integration due to a direct relationship between the fuel transport system, storage solution, and refuelling system. • Refuelling requirements: Pertains to and dictates how fuel is transferred from the bunker storage system to the physical vessel through trucks, piping to enable operation.

The themes identified focused on life cycle requirements (both functional and technical) necessary for eventual H2 maritime vessel realisation. For this careful consideration was paid to not only to the general response, but also how focus group participants responded.

Based on the outcomes it was confirmed that there is a distinct lack of requirements that support the development of sustainable maritime vessels. Additionally, the life cycle phase with the greatest environmental impact (middle of life) which was identified in the literature, was found to be nearly untouched due to the multidimensionality (requires consideration of the vessel and the bunkering to support refuelling) of H2 vessels.

From this the following points were synthesised and confirmed as having a significant role in the development of sustainable vessels:

- increasingly long-life span of vessels
- increasing cost for new ship building
- high technical complexity
- highly interconnected components
- diminishment of common propulsion system platforms/components.

6 Functional and technical requirements for the use of hydrogen as a maritime fuel

The outputs from the literature review and focus group were consolidated to formulate a set of characteristics for MOL maritime system sustainability. When considering this phase of the life cycle, it is important to understand how the operations and value of the system adjust over time. Despite the ever-continued presence of change and a desire for all things preserve value, not all systems are well suited to be sustainable. In order to improve the related requirements related to maritime vessels both technical and functional requirements need to be considered.

The basis for the requirements presented in Subsection 4.1 were formulated to address the lack of clear technical and functional requirements. Each requirements to be discussed is related to the to the long-term sustainability of the vessel and focus on the middle of life phase (Section 4) and relates to the complete vessel life cycle. This was done to provide for a structured solution that would allow for engineers/designers to develop sustainable vessels. The requirements detailed in this section were developed according to the outcomes derived from the literature review (Section 3) and focus group (Section 4).

6.1 Life cycle requirements

Based on the outcomes from the literature review and the focus group the MOL represented the largest area impacted by maritime systems. This phase includes the deployment, utilisation, and maintenance of the maritime vessel. Due to active utilisation, the work performed during the BOL is realised and the true life of the system is underway. In the MOL phase the logistics, emissions, operations, harbouring, and bunkering that facilitate the operation can be evaluated, retrofitted, or left alone. The distinction allowing for MOL to be strengthened through specific requirements resides in the real need to address and improve the most impactful aspect of the ship's life. While many aspects of a vessel can be independently studied only through the consideration of the ecological impact caused during the middle of life can a truly sustainable vessel be developed.

Among the existing requirements and regulations presented in Section 3, additional requirements need to be considered in relation to the sustainable introduction of hydrogen-based fuel in passenger' vessels. Given the system's intrinsic complexity, different functional and technical requirements are different in relation to the different vessels needs and operational profiles. Those requirements for the different operational profiles shall be a qualitative and/or quantitative measure to indicate how well each vessel functions.

a *Environmental requirement:* Within this study, environmental requirements refer to the different operational modes mentioned above are mainly affected by the waters and sea's conditions in which the vessel is required to perform. The environmental requirements have been defined as the environmental conditions to be encountered by the system in its different operational modes. This should address the natural environment (e.g., wind, rain, temperature, fauna, salt, dust, radiation, etc.), induced and/or self-induced environmental effects (e.g., motion, shock, noise, electromagnetism, thermal, etc.), and threats to societal environment (management of pollution sources and its consequences on natural environment and human health). The system shall meet essential requirements for safety, health, environmental and consumer protection, which are the following:

  - type of voyage (intended use)
  - wind speed
  - waves height
  - saline atmosphere.

b *Operational and logistical requirement:* The operational and logistical requirements (technical and functional) define the operational conditions or properties that are required for the system to operate or exist. This type of requirement includes human factors, ergonomics, availability, maintainability, and reliability. In relation to the maritime sector, the following interrelated parameters are critical, as any change leads to propagation in the requirements attributed to the inherent tight coupling of the related subsystems:

  - cruising speed
  - nautical miles
  - operational frequency
  - fuel autonomy
  - energy demand.

c *Safety requirements:* Safety requirements consider hazards associated with physical layout, operation and maintenance following any reasonably foreseeable failure. It is important to use acceptable and recognised risk analysis techniques to define safety requirements useful to set the safety technical specifications that can mitigate and eliminate risks wherever possible: the final output of safety requirements will be a safety plan applicable to the vessels with the same features of scenarios ones: it will be a living document that should contain tools for control and eliminate hazards and mitigation measures to keep the risk at an acceptable level. The risks are to be analysed using acceptable and recognised risk analysis techniques, and loss of function, component damage, fire, explosion, and electric shock are as a minimum to be considered. The analysis is to ensure that risks are eliminated wherever possible. Risks which cannot be eliminated are to be mitigated as necessary. Computing simulations and laboratory tests are among the ongoing activities. A safety plan supported by experimental data by laboratory and simulation studies will be developed and will include:

- hazard identification (HAZID) technique, conducted to identify potential hazards
- hazard and operability (HAZOP) study, conducted in order to identify and evaluate hazards that may represents risks to personnel or equipment
- failure mode and effects analysis (FMEA) may also be used to demonstrate that any single failure will not lead to an undesirable event.

d *Transportation requirements:* Based on location, demand, and the operational profile of the vessel scenario hydrogen fuel transport can be achieved through overland truck, vessel to port, or pipelines. However, due to high demand variability, and the fact that hydrogen higher energy density than other fuels, the main problem with hydrogen is one of low volumetric energy density (which requires large transfers). Key objectives of transportation requirements are to ensure the sustainable regular and predictable delivery of fuel to prevent shortages and the standstill of vessels in port. This requires:

- transfer method environmental impact (pipeline, truck transport emissions)
- suitability to integrate into existing port infrastructure
- proximity to fuel suppliers.

e *Storage requirements:* Related to fuel storage bunkering are determined by the demand, and vessel scenario requirements. Based on the H2 fuel demand supply at present a scalable solution should consider support for at a minimum two weeks per suitable vessel. In consideration of the storage capacity, the storage of compressed has distinct cost advantages for scenarios with low demand. In the event of demand increase liquid hydrogen storage would be the most viable fuel source, due to leaks being less frequent with larger tanks, fewer valves, and lower pressure. Leaks from high pressure tanks can be more severe (larger amounts of gas) and happen more often than for lower pressure tanks for that reason. Based on such consideration the following aspects should be evaluated:

- storage integrity
- storage capacity
- storage connectors
- storage ventilation.

f *Infrastructure requirements:* Should be ensured to guarantee safety, operational efficiency, and integration due to a direct relationship between the fuel transport system, storage solution, and refuelling system. The technical infrastructure requirements should consider no less than:

- H2 supply transfer process (fuel transport)

- ventilation and safety
- accessibility and pathways to facilitate fuel transport, and refuelling
- machinery and H2 piping, equipment, or consumers.

g *Refuelling requirements:* Ship and infrastructure design is affected by hydrogen storage option: due to LH2 and/or GCH2 being a preferred fuel source. Refuelling functional and technical requirements should consider:

- fuel off-loading
- connectors
- transfer speed and volume
- safety.

7 Discussion

The objective of this article was to facilitate the development of technical and functional requirements capable of supporting the realisation of sustainable maritime vessels. The article presented the main life cycle phases, considerations present and targets to facilitate realisation, as well as the gaps in current publications.

From this research, in response to Research Question 1, it was found that when considering the most appropriate and valuable phase of a vessel's life cycle, while each has a real impact, the MOL is both the longest lasting, environmentally impactful, and capable of value extension. Additionally, from the analysis, of the focus groups responses the shift towards H2 and renewable fuels will not only introduce an economic opportunity in the industry, but also a challenge to retrofit vessels using commercially available carbon neutral propulsion systems. In such a dynamic and fast-changing technological area, maritime vessel life cycle management is more important than effort for the efficient management, of ships. As the technologies and solutions being developed represent the greatest shift in the industry since the departure from wind to combustible fuels.

This article also proposed a set of requirements that should be considered to address the realisation of hydrogen powered vessels, as specified by Research Question 2. The process of change requires a high-level conceptualisation of the multiple dimensions and elements that will determine the successfulness sustainable vessel development. The recent and continued development of the IGF code and ISO for H2, shows that the concept of H2 is becoming both more commercially relevant and that technologically possible for such a propulsion technology shift. However, the gaps remaining demand more specific test cases to better evaluate and establish pre-normative standards to facilitate ultimate realisation.

8 Conclusions

Sustainability, life cycle management and requirements are not a new concept. However, when confronted with new technical solutions, as referenced with the case of hydrogen propulsion it is critical that the entire system be considered so that most detrimental environmental phase of the vessel life can be mitigated. The objectives established Section 2 of this paper were guided by the principal of measure twice and cut once. Where through verification and careful planning a system can be analysed and constructed so that the most impactful areas can be planned to create a valuable and desirable maritime vessel.

Historically and according to the literature many customers and stakeholder identify and request technologies and solutions they perceive as being most vital to their business's success. However, when new sustainability goals and tighter environmental regulations it is vital that vessels operate throughout their life cycle in a way that helps resolve uncertainties.

In response to RQ1 the largest environmental impact during a ships life cycle was MOL. Looking at the trend in this research field and value of PLM it is critical that the industry understand the effect of environmental change beyond conceptualisation and begin looking at the real and direct effect that alternative fuels and requirements engineering has on development. In response to RQ2 by addressing and formulating a set of functional and technical requirements (design and bunkering) applicable to the MOL engineers can better support the realisation of hydrogen powered vessels and increase overall sustainability to meet UN SDGs.

Despite the immense practical value of these requirements the true potential will only be realised when the maturity level and competencies of the industry have increased to support greater renewable energy adoption. Therefore, future research will focus on advancing our knowledge in two critical areas:

1 the development of sustainable bunkering systems for hydrogen powered vessel, that provide for efficient and predictable operation

2 the comprehensive evaluation of hydrogen powered vessel performance, cost, and life cycle impact (from energy source generation, BOL, MOL and EOL).

References

Abramovici, P.M. and Schulte, S. (2007) 'Optimising customer satisfaction by integrating the customer's voice into product development', *International Conference on Engineering Design, ICED'07*.

Al-Enazi, A.A., Okonkwo, E.C., Bicer, Y. and Al-Ansari, T. (2021) 'A review of cleaner alternative fuels for maritime transportation', *Energy Reports*, Vol. 7, pp.1962–1985.

Bilgili, L. (2021) 'Comparative assessment of alternative marine fuels in life cycle perspective', *Renew. Sustain. Energy Rev.*, Vol. 144, No. C.

Braun, V. and Clarke, V. (2006) 'Using thematic analysis in psychology', *Qual. Res. Psychol.*, Vol. 3, No. 2, pp.77–101.

DESA (2022) *UN Department of Economic and Social Affairs Sustainable Development Goals*.

Dinu, O. and Ilie, A.M. (2015) 'Maritime vessel obsolescence, life cycle cost and design service life', in *IOP Conference Series: Materials Science and Engineering* [online] https://doi.org/10.1088/1757- 899X/95/1/012067.

Erbach, G. (2020) 'Reducing CO_2 emissions of maritime transport', *Eur. Parliam. – Pleanary Sess*.

Eyring, V., Köhler, H.W., van Aardenne, J. and Lauer, A. (2015) 'Emissions from international shipping: the last 50 years', *J. Geophys. Res.*, Vol. 110, p.17305, https://doi.org/10.1029/2004JD005619.

Farr, J.V. (2012) ‘Life cycle cost considerations for complex systems’, *Syst. Eng. – Pract. Theory* [online] https://doi.org/10.5772/32063.

Fuel Cells and Hydrogen (FCH) Joint Undertaking (2019) *Hydrogen Roadmap Europe* [online] https://doi.org/10.2843/249013.

Garetti, M. and Terzi, S. (2003) ‘Product lifecycle management: definizione, caratteristiche e questioni aperte’, in *Tech. Rep.*, Politecnico di Milano, p.16.

Gratsos, G.A., Psaraftis, H.N. and Zachariadis, P. (2010) ‘Lifecycle CO_2 emissions of bulk carriers: a comparative study’, *Trans. R. Inst. Nav. Archit. Part A Int. J. Marit. Eng.*, Vol. 152 [online] https://doi.org/10.3940/rins.ijme.2010.a3.176.

Halff, A., Younes, L. and Boersma, T. (2019) ‘The likely implications of the new IMO standards on the shipping industry’, *Energy Policy*, Vol. 126, pp.277–286 [online] https://doi.org/10.1016/j.enpol.2018.11.033.

Hwang, S.S., Gil, S.J., Lee, G.N., Won Lee, J., Park, H., Jung, K.H. and Suh, S.B. (2020) ‘Life cycle assessment of alternative ship fuels for coastal ferry operating in Republic of Korea’, *J. Mar. Sci. Eng.*, Vol. 8, pp.1–18 [online] https://doi.org/10.3390/JMSE8090660.

IMO (2019) *International Maritime Organization – Interim Guidelines for Mass Trials*.

IMO (2022a) *MARPOL Annex VI, International Convention for the Prevention of Pollution from Ships*.

IMO (2022b) *Initial GHG Strategy* [online] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-fromships.aspx (accessed 30 January 2022).

INCOSE (2011) *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 3.2.2, International Council on Systems Engineering (INCOSE), INCOSE-TP-2003-002-03.2.2, San Diego, CA, USA.

Keane, A., Gaspar, H.M. and Brett, P.O. (2015) ‘Epoch era analysis in the design of the next generation offshore subsea construction vessels’, *2015 10th Syst. Syst. Eng. Conf. SoSE 2015*, pp.322–327 [online] https://doi.org/10.1109/SYSOSE.2015.7151911.

Koroneos, C., Dompros, A., Roumbas, G. and Moussiopoulos, N. (2004) ‘Life cycle assessment of hydrogen fuel production processes’, *Int. J. Hydrogen Energy*, Vol. 29, pp.1443–1450 [online] https://doi.org/10.1016/j.ijhydene.2004.01.016.

Luglietti, R., Wurst, S., Sassanelli, C., Terzi, S. and Martín, C.M. (2018) ‘Towards the definition of specialized vessels’ model’, in *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*.

Montwiłł, A., Kasińska, J. and Pietrzak, K. (2018) ‘Importance of key phases of the ship manufacturing system for efficient vessel life cycle management’, *Procedia Manuf.*, Vol. 19, pp.34–41 [online] https://doi.org/10.1016/j.promfg.2018.01.006.

Naderifar, M., Goli, H. and Ghaljaei, F. (2017) ‘Snowball sampling: a purposeful method of sampling in qualitative research snowball sampling: a purposeful method of sampling in qualitative’, *Strides Dev. Med. Educ.* [online] https://doi.org/10.5812/sdme.67670.

NASA (2007) *Systems Engineering Handbook*, Revision 1, National Aeronautics and Space Administration (NASA), NASA/SP-2007-6105, Washington, DC, USA.

Olmer, N.B.C.B.R.X.M.D.R.T.S. (2017) *Greenhouse Gas Emissions from Global Shipping, 2013–2015*.

Ramirez-Peña, M., Fraga, F.J.A., Salguero, J. and Batista, M. (2020) ‘Assessing sustainability in the Shipbuilding Supply Chain 4.0: a systematic review’, *Sustain.*, Vol. 12 [online] https://doi.org/10.3390/SU12166373.

Ricci, N., Rhodes, D.H., Ross, A.M. and Fitzgerald, M.E. (2013) ‘Considering alternative strategies for value sustainment in systems-of-systems’, *SysCon 2013 – 7th Annu. IEEE Int. Syst. Conf. Proc.*, pp.725–730 [online] https://doi.org/10.1109/SysCon.2013.6549963.

Sassanelli, C., Pezzotta, G., Pirola, F., Sala, R., Margarito, A., Lazoi, M., Corallo, A., Rossi, M. and Terzi, S. (2018) ‘Using design rules to guide the PSS design in an engineering platform based on the product service lifecycle management paradigm’, *Int. J. Prod. Lifecycle Manag.*, Vol. 11, pp.91–115 [online] https://doi.org/10.1504/IJPLM.2018.092826.

Sassanelli, C., Pezzotta, G., Pirola, F., Terzi, S. and Rossi, M. (2016) 'Design for product service supportability (DfPSS) approach: a state of the art to foster product service system (PSS) design', *Procedia CIRP*, Vol. 47, pp.192–197 [online] https://doi.org/10.1016/j.procir.2016.03.233.

Stanić, V., Hadjina, M., Fafandjel, N. and Matulja, T. (2018) 'Toward Shipbuilding 4.0 – an Industry 4.0 changing the face of the shipbuilding industry', *Brodogradnja*, Vol. 69, pp.111–128 [online] https://doi.org/10.21278/brod69307.

Sullivan, B.P., Desai, S., Sole, J., Rossi, M., Ramundo, L. and Terzi, S. (2020) 'Maritime 4.0 – opportunities in digitalization and advanced manufacturing for vessel development', in *Procedia Manufacturing*, pp.246–253. Elsevier BV [online] https://doi.org/10.1016/j.promfg.2020.02.078.

Sullivan, B.P., Rossi, M. and Terzi, S. (2018a) 'A customizable lean design methodology for maritime', in *5th IFIP WG 5.1 International Conference*, Springer, Turin, Italy, pp.508–519 [online] https://doi.org/10.1007/978-3-030-01614-2_47.

Sullivan, B.P., Rossi, M., Sassanelli, C., Luglietti, R., Ramundo, L. and Terzi, S. (2018b) 'LINCOLN integrated solution supporting the design of specialized connected vessels', in *XXIII Summer School 'Francesco Turco' – Industrial Systems Engineering LINCOLN*, pp.250–256.

Sullivan, B.P., Rossi, M. and Terzi, S. (2018c) 'A review of changeability in complex engineering systems', in *IFAC-PapersOnLine*, pp.1567–1572, Elsevier BV [online] https://doi.org/10.1016/j.ifacol.2018.08.273.

Terzi, S., Bouras, A.A., Dutta, D., Kiritsis, D., Garetti, M. and Kiritsis, D. (2010) 'Product lifecycle management – from its history to its new role', *Int. J. Prod. Lifecycle Manag.*, Vol. 4, pp.360–389 [online] https://doi.org/10.1504/IJPLM.2010.036489.

The European Clean Hydrogen Alliance (n.d.) *Internal Market, Industry, Entrepreneurship and SMEs* [online] https://ec.europa.eu/growth/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance_en (accessed 12 February 2022).

UN Sustainable Transport (2021) *Sustainable Development.*

US Department of Defense Systems Management College (2001) *Systems Engineering Fundamentals* [online] https://doi.org/10.1016/j.cmpb.2010.05.002.

Vakili, S.V., Ölçer, A.I. and Schönborn, A. (2021) 'Identification of shipyard priorities in a multicriteria decision-making environment through a transdisciplinary energy management framework: a real case study for a Turkish shipyard', *J. Mar. Sci. Eng.*, Vol. 9 [online] https://doi.org/10.3390/jmse9101132.

Walden, E.S.E.P.D.D. and Roedler, E.K.J.F.R.D.H.T.M.S.G.J. (2015) *Systems Engineering Handbook* [online] https://doi.org/10.1016/0016- 0032(66)90450-9.

Wang, N.P.L.H. (2013) 'Long-term potential for increased shipping efficiency through the adoption of industry-leading practices', *International Council on Clean Transportation*, 30 September.

Xing, H., Spence, S. and Chen, H. (2020) 'A comprehensive review on countermeasures for CO_2 emissions from ships', *Renew. Sustain. Energy Rev.*, Vol. 134, p.110222.