A critical review and normalization of the life cycle assessment outcomes in the naval sector. Bibliometric analysis and characteristics of the studies

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ABSTRACT

Most of the actual industrial research efforts are aimed at reducing environmental burdens associated with human activities in the context of sustainable development. This trend has become increasingly prevalent in the naval transportation sector shown by a growing number of scientific publications dealing with life cycle assessments of maritime-related activities. However, the life cycle assessment framework provides practitioners with a variety of alternatives for conducting the analyses, giving room for defining key factors, such as functional units, system boundaries, and impact assessment methods, among others. This lack of standardization resulted in a wide range of assumptions and findings that are seldom comparable. The goal of this review is providing a systematic literature analysis, focusing on the characteristics of life cycle assessments dealing with the environmental impacts of various maritime vessel categories. In the first part, a qualitative analysis of the available scientific literature has been performed, providing a bibliometric analysis and a general overview of the characteristics of the studies (*i.e.*, life cycle impact assessment methodologies, background data, and software tools used). The outcomes of the bibliometric analysis are then summarized and discussed to understand current practices and future trends in this field, providing the basis for the normalization phase of the results. The second section of the paper offers advice for naval practitioners on how to perform results normalization to produce comparable analyses. Two approaches for normalization have been proposed in the frame of this study: an "horizontal" one, which is based on vessel features and allows a comparison among different vessel typologies, and a "vertical" one that enables to fairly compare vessels of the same category to one another. In addition, each section reports the outcomes of greenhouse gas-related impact categories, which have been subjected to the proposed normalization procedure, along with the order of magnitude of the results for each life cycle phase. The overall work provides an overview of LCA impact results as well as a collection of procedures and recommendations for future life cycle assessments based on specific vessel types, in terms of functional unit selection, system boundary definition, impact assessment approach, presentation of the outcomes, and normalization basis.

Keywords:
LCA
Life cycle assessment
Life cycle analysis
Naval
Ship
Maritime

1. Introduction

The maritime transportation industry is undergoing a transformation to become more economically, socially, and ecologically sustainable. It is common knowledge that marine vessels' activities have significant environmental consequences such as greenhouse gas emissions, air pollution, underwater noise, oil contamination, etc. The International Maritime Organization (IMO) is responsible for the safety and security of global shipping, promoting several measures to protect the marine environment from the ecological impacts of shipping activities, *e.g.*, preventing emissions of GreenHouse Gas (GHG) (IMO - Marine Environment Protection Committee, 2020) or NOx (IMO - International Maritime Organization, 2019). As a result, in recent years, researchers, practitioners, and maritime firms have all employed a life cycle approach to examine the environmental risks related to goods transported by sea. Indeed, it is critical to examine both the shipping and shipbuilding characteristics in order to achieve a greener marine sector. The life cycle assessment (LCA) approach is consistent with the key concepts of green shipbuilding, which are represented by the so-called "triple R's": (i) reducing materials, energy consumption, and pollutant emissions during ship manufacturing, (ii) recycling almost all ship maintenance components, and (iii) reusing the majority of ship's materials during its disposal. The primary goal of green manufacturing is to

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Glossary

ADE	Abiotic Depletion of Elements
ADF	Abiotic Depletion of Fossil fuels
AP	Acidification Potential
CC	Climate Change
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand
CFC	ChloroFluoroCarbon
CPC	Central Product Classification
CTUe	Comparative Toxic Units ecotoxicity
CTUh	Comparative Toxic Units for human
DCB	DiChloroBenzene
ECA	Emission Control Area
EI99	EcoIndicator 99
EoL	End of Life
EP	Eutrophication Potential
ETP	EcoToxicity Potential
FD	Fossil Depletion
FETP	Freshwater EcoToxicity Potential
FEU	Freshwater EUtrophication
FU	Functional Unit
GHG	GreenHouse Gas
GWP	Global Warming Potential
HCE	Human Carcinogenic Effects
HCFC	HydroChloroFluoroCarbon
HNCE	Human Non-Carcinogenic Effects
HTP	Human Toxicity Potential
ILCD	International reference Life Cycle Data system
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IR	Ionising Radiation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquefied Natural Gas
LOP	Land Occupation Potential
LU	Land Use
MD	Metal Depletion
METP	Marine EcoToxicity Potential
MEU	Marine EUtrophication
MSETP	Marine Sediment EcoToxicity Potential
N.A	Not Applicable – Not Available
NMVOC	Non-Methane Volatile Organic Compounds
NLT	Natural Land Transformation
ODP	Ozone Depletion Potential
PM	Particulate Matter
PMFP	Particulate Matter Formation Potential
POCP	Photochemical Ozone Creation Potential
POFP	Photochemical Oxidant Formation Potential
RDE	Resource Depletion of Elements
RDF	Resource Depletion of Fossil fuels
RE	Respiratory Effect
RoRo	Roll-on/roll-off
S	Smog
SLCA	Social Life Cycle Assessments
TETP	Terrestrial EcoToxicity Potential
TEU	Terrestrial EUtrophication
TRACI	Tool for Reduction and Assessment of Chemicals and other environmental Impacts
TTW	Tank-To-Wake
ULCC	Ultra Large Crude Carrier
VLCC	Very Large Crude Carrier
VOC	Volatile Organic Compound
WTT	Well-To-Tank
WTW	Well-To-Wake
WUD	Water Use Depletion

Locations

CAN	Canada
CHN	China
DEU	Germany
DNK	Denmark
ESP	Spain
EU	Europe/European
FRA	France
GBR	Great Britain
GRC	Greece
ITA	Italy
KOR	South Korea
LTU	Lithuania
NLD	Netherlands
NOW	Norway
QAT	Qatar
PER	Perù
PRT	Portugal
SLO	Slovenia
SWE	Sweden
TUN	Tunisia
TUR	Turkey
USA	United States of America
VNM	Vietnam

reduce material waste while also picking new and more sustainable materials that can bring benefits, such as nano-engineered thermoplastic polymers (Mio et al., 2021) or greener processing methods and improved life cycle assessment outcomes.

Since the growing interest of the international community in environmental pollution and the rise of the LCA methodology in the last two decades, several works have been developed with the goal of understanding, characterizing, and implementing corrective actions to offshore operations performed by marine vessels. LCA is a technique for assessing the possible environmental implications and resources required throughout a product's life cycle, beginning with raw material acquisition and continuing with manufacturing and consumption phases to waste disposal (The International Standards Organisation, 2021a). The results of life cycle analyses are reported in a variety of impact categories, with the goal of evaluating the whole range of ecological consequences associated with the life cycle of the product under investigation. The LCA framework entails four phases of implementation, which are briefly described underneath. The first is the “Goal and Scope,” which allows describing the study's goal, target readers, functional unit, system boundary, data source quality, and approach assumptions and limitations. The second phase, called “Life Cycle Inventory” (LCI), involves gathering the mass and energy balances of the product system under investigation (Rebitzer et al., 2004). Following that, the inventory data are used in the “Life Cycle Impact Assessment” (LCIA) stage, which links them to specific environmental impacts using well-established emission factors. Finally, the “Interpretation” phase uses discretionary sensitivity and uncertainty analyses to interpret the data produced in the previous phases (Pennington et al., 2004). In the maritime sector, LCA-based studies have been conducted for a variety of shipping operations, including passenger transportation (ferries), commodities and fuels transportation (tankers and cargo vessels), pleasure and recreational activities (yachts), and fishing, among others. LCA has grown in maturity and methodological robustness over time, resulting in the development of an international standard (The International Standards Organisation, 2021b). However, the overarching framework for performing an LCA research provides practitioners with a variety of options for conducting the analysis. As noticed in the current literature, the lack of restrictions in constructing the LCA for the system of interest resulted in varied assumptions and outcomes. The disparity is caused primarily by the functional unit's definition, assumptions about the product's life cycle, differences in system boundaries, environmental indicators selection, and outcomes reporting. Inconsistencies persist even for the same product, making it difficult to compare findings and identify patterns in the shipbuilding industry. For instance, before the ship is delivered, the shipbuilding process includes multiple operations (raw materials acquisition and refining, component fabrication, vessel assembly, sea trials, etc.), and the available studies do not always declare what is included or not. Some attempts at sectoral standardization have been made, although they have mostly focused on specific tasks, such as developing a holistic strategy (Fet et al., 2013), data retrieval and organization (Favi et al., 2019; Nam et al., 2016), the development of a dedicated tool (Prinçaud et al., 2010) or the definition of new impact eco-financial indicators (Ytreberg et al., 2021). As a result, there is room for improvement in the application of the LCA framework in shipbuilding and vessel operations.

Based on a scientific literature investigation of the works already published, this critical review aims to provide assistance to naval practitioners willing to perform an LCA in the naval sector. The objective of the first part is presenting a bibliometric analysis of the research works in the context of LCA for different maritime vessel categories. The review outcomes provide a general overview of the main trends in this sector concerning LCIA methodologies, background data, and software tools that were adopted so far. Outcomes are then summarized with the aim to provide specific benchmarks for the development of two normalization procedures. The second part (Mio et al., 2022) includes a set of recommendations for LCA methodological choices in order to promote the alignment of existing and future studies in this field on a common ground. The results of greenhouse gas-related effect categories are then shown, together with the order of magnitude of the results for each life cycle phase, after they have been subjected to the proposed normalizing procedure. As a result, future studies will be able to determine some benchmark values to compare against.

2. Methodology for the selection of contributing assessments

The approach used to reach the review's goal is based on a systematic literature review based on a Scopus database search, which was conducted on June 29th, 2021. Scopus database was selected due to its comprehensive collection of journals belonging to the naval field. The search was restricted to English-language publications available in peer-reviewed journals. The keywords chosen to query the database can be seen in Fig. 1.

To select the relevant articles, the search was conducted using the following keywords in combination with Boolean operators: ((“Life Cycle Assessment” OR “Life Cycle Analysis” OR “LCA”) AND (“Naval” OR “Ship” OR “Maritime”)). A total of 943 articles were found in Scopus. The results have been thoroughly refined using a series of filters, as presented hereafter:

- only documents from research and review articles from peer-reviewed journals in English were included. Duplicated documents, book chapters, and grey literature (*i.e.,* reports, dissertation, and theses) were excluded;
- conference proceedings published on special issues of peer-review journals were included;
- the articles not related to the topic and scope of this review were ruled out through the analysis of titles, keywords, and abstracts.

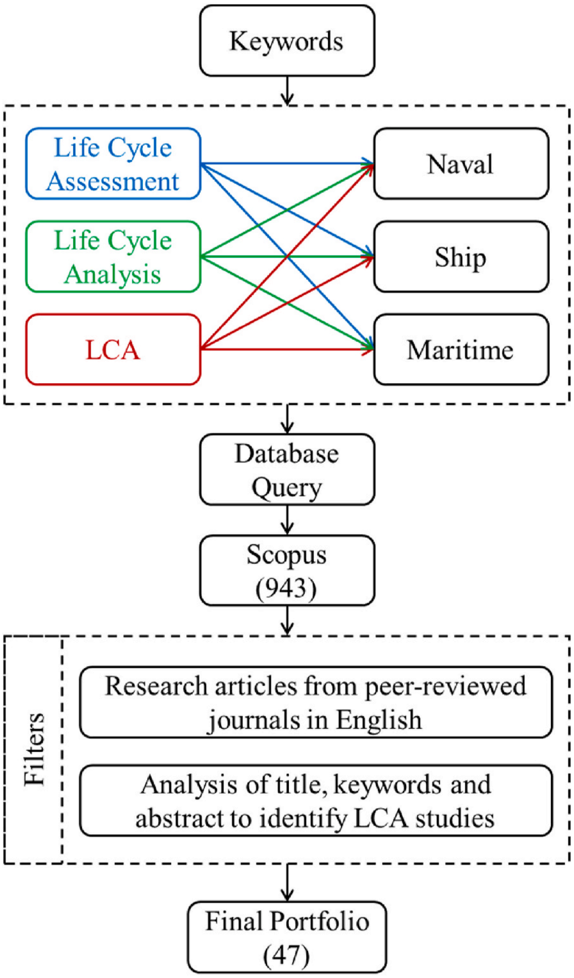

Fig. 1. Decision procedure flowchart.

As a result, only full articles and conference proceedings from peer-reviewed journals were examined, resulting in a total of 47 publications.

A further refinement based on the boundaries of the product systems has been performed, discerning between two major trends: (i) system boundary comprehending at least one component of the vessel (*e.g.,* hull, power system, coating, naval systems, etc.); (ii) system boundary including exclusively the supply chain of fuels adopted in the naval sectors, *i.e.,* Well To Wake (WTW) approach. The former studies implemented a cradle-to-gate or cradle-to-grave perspective including the entire vessel or some of its components within the system boundary, while the latter disregarded any part of the vessel in focusing on the fuel life cycle, considering its supply chain (Well To Tank – WTT) and its consumption during the operational phase of the vessel (Tank To Wake – TTW). Even though both product systems are of interest to the naval sector, they deal with different perspectives, making any comparison of the two groups' results unfeasible. Therefore, a review of the available literature for each separate scope appears to be more practical, with the purpose of offering an overview of prior authors' benchmark values in each domain. Hence, this review focuses on the products whose system boundaries comprehend at least one component of the vessel under study. Additionally, the assessments focused exclusively on Life Cycle Costing (LCC) or Social Life Cycle Assessment (SLCA) have been excluded, as they are outside the scope of this review.

The following sections deal with the qualitative analysis of the literature available, exhibiting the main features characterizing the LCA publications in the maritime field. The features examined in the papers' portfolio (47 articles) comprehend the number of documents per year, the authorship, the publication source, the geographic location (country) where the research was conducted, the number of citations per article, the LCIA methods and impact categories, the inventory database, and the software tool for calculation.

Despite the authors do not claim this study to be free of limitations nor exhaustive, this review brings a useful contribution to the addressed literature body. To the best of the authors' knowledge, no studies investigating the features of LCA in the naval sector have been published yet. In the present research work, several contributions will be provided:

- a qualitative analysis of the main features of the scientific literature dealing with LCA in the naval sector;
- a quantitative indication of the environmental impact results (*e.g.*, global warming potential) for each vessel type among available studies, as presented in the second part (Mio et al., 2022);
- some recommendations towards a standardization of the future life cycle assessments, in terms of the choice of functional unit, system boundaries, LCA approach, and presentation of the results.

3. Bibliometric analysis

3.1. Number of publications per year

Following the outcomes of the literature selection process (final portfolio), it is noteworthy to remark that the relevant literature covers a limited timeframe beginning in 2009. Fig. 2 reports the distribution of papers considering the publication years and the number of cumulative citations during this period.

The overall trend increased in the last years and more than 80% of the retrieved papers were issued in the last six years. Although the graph shows a scattered distribution of papers, ranging from 0 to 11 for each year, the mean value for the overall period (2009–2021) is approx. 3.5 papers per year. Focusing on the earlier period (2009–2014) the mean value is slightly higher than 1 paper per year, while during last the six years the mean value rises to approx. 5.5 papers per year. The result of this analysis highlights that there is a growing interest in the development of LCA studies for marine vessels, which is confirmed by the increasing trend of citations in the last five years. This finding is in line with the industrial demands to develop more sustainable systems, capable of meeting new industry requirements and tackling the issue related to marine pollution and the emissions from this sector. Furthermore, the increasing use and acceptance of LCA approach contribute significantly to this goal.

3.2. Publication source

The current study considers 47 papers, published in 22 different scientific journals or peer-reviewed conference proceedings. The top 4 journals, which cover approx. 50% of the overall number of papers (24 papers out of 47), are characterized by having at least five articles each (Table 1). "Journal of Cleaner Production" is the journal with the highest number of papers, followed by "International Journal of Life Cycle Assessment", "Ocean Engineering" and "Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment". It is interesting to highlight the different topics covered by the above-mentioned journals. Indeed, papers published by the "International Journal of Life Cycle Assessment" are mostly related to fishery and LCA analysis of vessels belonging to fishing activities. On the other hand, works published in the other three journals belong to different types of vessels (*i.e.*, yacht, tugboat) and several vessel operations (*e.g.*, unconventional propulsion systems, alternative shipping fuels, use of scrubber systems, etc.).

The most relevant subject areas of the four journals are summarized in Table 1. Except for "Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment", which is Q2 for the Engineering topic, the rest of the journals are Q1 for all subject areas.

Table 1
Most significant journals, with at least five papers (sorted according to the number of documents considered in the review).

Journals	Subject category	Papers	Number of citations
Journal of Cleaner Production	Business, Management and Accounting Environmental Science Engineering Energy	8	138
Ocean Engineering	Engineering Environmental Science	6	92
International Journal of Life Cycle Assessment	Environmental Science	5	102
Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment	Engineering	5	20
Others	Various	23	328

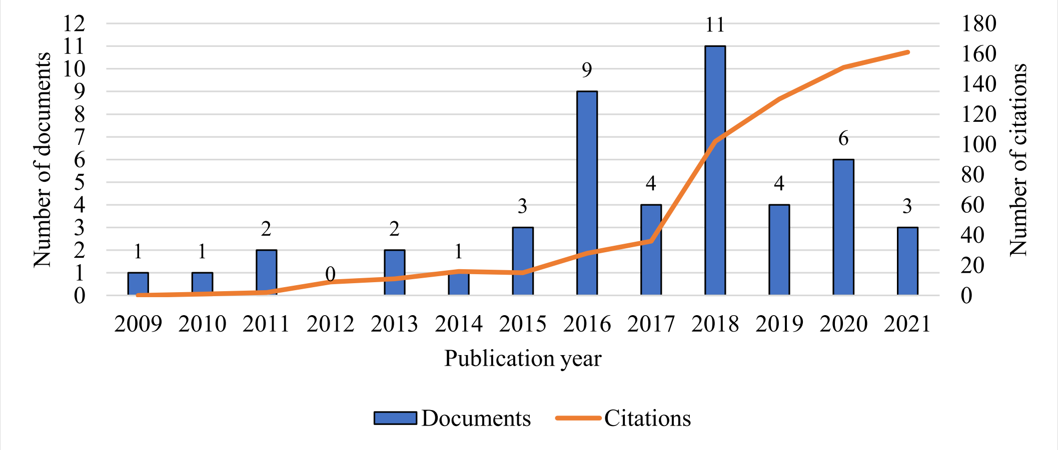

Fig. 2. Overview of the number of documents and cumulative citations through the years.

3.3. *Authorship and country co-occurrence*

The most productive authors are Zhou, P. (8 papers), Jeong, B. (6 papers), Wang, H. (5 papers), Favi, C. (5 papers), Germani, M. (5 papers), Campi, F. (4 papers), and Dong, D.T. (4 papers). The most active countries on LCA analysis of maritime vessels and systems are located in Europe and Asia, while American and African countries present only a few works on this topic. Among the EU countries, the most productive ones are Great Britain (13 papers), followed by Italy (8 papers), France (5 papers), and Sweden (3 papers). China (10 papers), Vietnam (5 papers), and Turkey (4 papers) are the most productive Asian countries, as shown in Fig. 3.

Taking into consideration first authors only, researchers from European universities cover approx. 78% of the published articles on this topic, researchers from Asian universities cover approx. 14%, while researchers from American universities cover approx. 8%. It is worth to highlight that the quantity of cooperation among universities belonging to different countries is high and they account for approx. 32% (16 papers have been jointly written by two or more researchers from different countries and universities). The most active university on this topic is the University of Strathclyde (GBR) with 8 issued papers, followed by Parma University/Polytechnic University of Marche (ITA) and Vietnam Maritime University (VNM) with 5 issued papers, and Harbin Institute of Technology (CHN) with 4 issued papers. Fig. 4 depicts the geographical distribution of the publications, with the true physical location of each country. The size of each nation is determined by the number of documents containing at least one affiliation inside the country, and they are coloured according to the continent to which they belong. The arrows represent documents with shared authorship between countries, and the thickness of the arrows increases as the number of shared publications increases.

4. Main publication trends

The first part of this literature review focuses on identifying the main features and publication trends towards a normalization process of life cycle analysis in the maritime sector. Section 4.1 investigates the functional units, system boundaries, and allocation methods used in the analysed works. Section 4.2 reports life cycle impact assessment methods and indicators used in this field, while section 4.3 analysed background data e software tools adopted to carry out the analyses.

4.1. *Functional unit, system boundaries, and allocation method*

Several assumptions were introduced to conduct LCA analyses in a complex sector such as the naval one, starting from the definition of the functional units (FUs), as reported in Table 2. There is a notable lack of a comprehensive study that categorizes and prioritizes the various functional units and systems used in the maritime industry for LCA assessments. This review addresses this need, offering a starting point for future LCA research in the maritime industry to the scientific community. Beyond the type of vessel and its peculiarities, the functional units mostly differ in terms of the service lifetime and the lifecycle phases considered in the analysis. For instance, the vessel lifetime may take a wide range of values due to different manufacturing materials or different vessel applications, and consequently, the LCA outcomes may be hardly comparable. The life cycle phases considered in the analyses face an analogous issue. Despite the fact that the bulk of study publications attempted to conduct cradle-to-grave investigations, some life cycle phases, such as maintenance or end-of-life (EoL), are usually overlooked. Detailed information about the system boundaries considered in the works analysed in this review is reported in Supplementary Materials.

Another key element of articles in this field is the authors' choice of the allocation system model, which should match the declared assessment's goal. As a result of the use of various allocation models among the published assessments, the outcomes are inconsistent and incomparable, particularly when dealing with the EoL phase. Most of the works analysed in this review did not clearly report the allocation model adopted to conduct the LCA analysis. Following a thorough examination of each publication, the "Allocation Cut-off" model was the most widely used strategy, with only a few adopting the "Allocation at the Point of Substitution" model and none using the "Consequential" one. Based on this first analysis, as a general guideline, the selection of a coherent allocation model is essential to standardize the results of LCA analyses in the naval field, with the "Allocation Cut-off" as the most suitable model for this product category. The FU definition should be lifetime-independent, which implies that the operational phase outcomes shall be reported on a yearly basis to allow for future comparisons. Furthermore, the adoption of a cradle-to-grave approach is required to normalize the results across the many investigations, with the outcomes organized to highlight the impacts of the various stages of the vessel's lifecycle (*i.e.,* materials & manufacturing, operation, maintenance, and EoL).

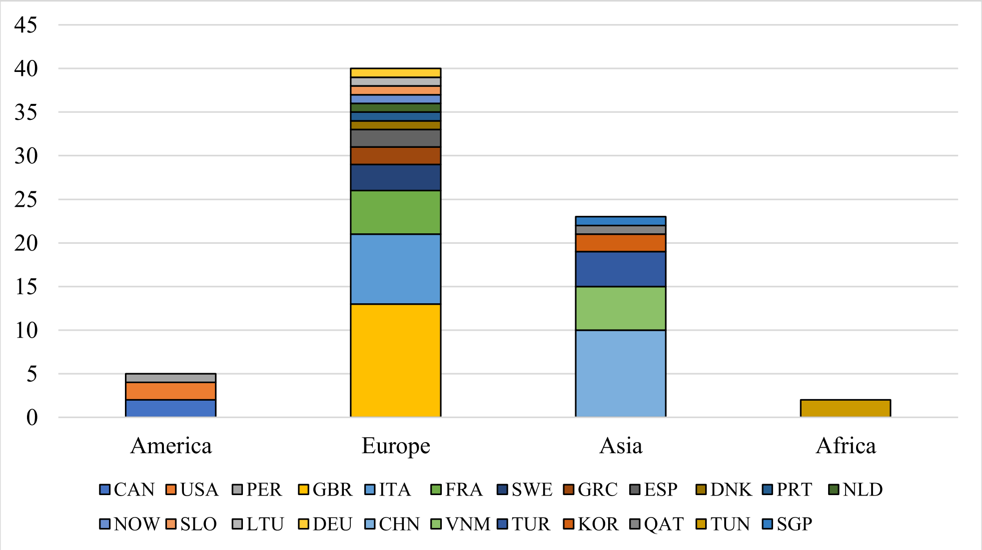

Fig. 3. Number of publications per continent.

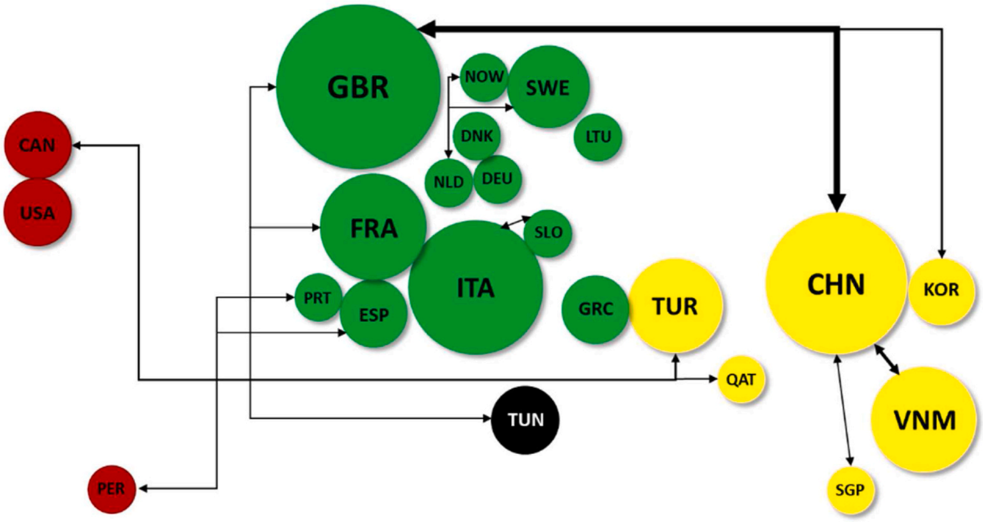

Fig. 4. Geographical distribution of the issued papers.

Additionally, the vessel category is crucial for establishing a suitable and consistent FU. When the function and performance of the product system under consideration are both consistent, the normalizing procedure stands to reason. It is evident from the lifecycle assessments examined for this study that the majority of the FUs were defined with the intention of analysing a specific vessel, or at the very least a certain vessel with alternative systems (see Table 2). For cargo, ferry and fishing vessels, whose range of operations is more readily discernible, a normalization basis has already been proposed (*i.e.,* one ton of bulk cargo over one km transported by sea for the cargo vessel, one passenger over one km transported by sea for the ferry or 1 ton of landed fish for the fishing vessel). Based on the function provided by each vessel category, a normalization basis for the life cycle assessment outcomes is essential to enable a clear comparison among alternative solutions and to identify the main cause of criticalities. This topic has been discussed in detail in the second part of this review (Mio et al., 2022).

4.2. *Life cycle impact assessment methods*

The adoption of well-established impact categories allows for the quantification of the environmental impacts caused by shipping activities. Numerous impact categories are available in the literature, each one related to specific environmental compartments and harms. Every substance known to have a harmful effect on the compartment addressed by a specific impact category is assigned a characterisation factor that is proportional to the substance's impact. The impact categories have been embedded into several LCIA methods, which include a variety of impacts, in order to present a comprehensive picture. The most used methods in the naval sector are CML-IA (de Bruijn et al., 2002), EcoIndicator 99 (EI99) (Goedkoop and Spriensma, 2000), ILCD (EC-JRC, 2012), Impact 2002+ (Jolliet et al., 2003), ReCiPe (Huijbregts et al., 2017) both midpoint and endpoint, and TRACI (Bare, 2011). Fig. 5 shows the occurrence of each method along with direct emissions, *i.e.,* where the authors did not use any LCIA methods, but rather present the direct emissions of the life cycle.

Even if some of the impact categories are similar or address the same issue, each LCIA method has its own list of impact categories. The ones included within the LCIA methods considered are briefly presented:

- Abiotic (or Resource) Depletion of Elements (ADE, RDE) and Metal Depletion (MD): reflects a decline in the amount of non-renewable and renewable abiotic resources accessible for human use. It is quantified by CML-IA (CML-ADE) and ILCD (ILCD-ADE) using [kg Sb-eq], while ReCiPe (Re-MD) focuses on the depletion of metals only, using [kg Fe-eq].
- Abiotic (or Resource) Depletion of Fossil Fuels (ADF, RDF) and Fossil Depletion (FD): represents a decrease in the amount of fossil fuels available for human use. It is used by CML-IA (CML-ADF measured in MJ), ReCiPe (Re-FD in [kg oil-eq]) and ILCD (ILCD-RDF in [MJ]).
- Acidification Potential (AP): reflects the detrimental acidic consequences of the life cycle emissions on atmosphere, water or soil. It is comprehended within CML-IA (CML-AP) and ReCiPe (Re-AP), where is measured in [kg SO_2-eq], and within ILCD (IL-AP) and TRACI (TR-AP), where is expressed in [mol H^+-eq].
- Climate Change (CC)/Global Warming Potential (GWP): represents the effects of greenhouse gas (GHG) emissions on heat absorption, leading in higher temperatures in the lower atmosphere and climate change, which is a severe danger to world ecosystems. It is commonly calculated based on the GWP over a 100-year time horizon (IPCC-GWP100) according to the UN Intergovernmental Panel on Climate Change (Stocker et al., 2013). It is expressed in [kgCO_2-eq] and calculated by CML-IA (CML-GWP), ILCD (ILCD-CC), ReCiPe (Re-CC) and TRACI (TR-GWP).
- Cumulative Energy Demand (CED): represents the amount of energy (*e.g.,* fossil fuels, electricity) required during the life cycle of the product and is expressed in MegaJoules [MJ].
- Ecotoxicity Potential (ETP): depicts hazardous chemicals' detrimental impact on various natural compartments, including marine (METP), freshwater (FETP) and terrestrial (TETP) ecosystems and marine sediments (MSETP). CML-IA and ReCiPe adopts USES-LCA method (Van Zelm et al., 2009), which defines the fate, exposure and effects of toxic emissions related to each substance involved in the life cycle. They express the indicators CML-METP, CML-MSEPT, CML-FETP, CML-TETP, Re-METP, Re-FETP, Re-TETP using [kg1, 4-DCB-eq], where DCB stands for dichlorobenzene. TR-ETP and ILCD-FETP adopt [CTUe], instead.
- Eutrophication Potential (EP): shows the detrimental consequences of nitrogen and phosphorus discharge into the ecosystem, in terms of overstimulating algal and aquatic plant growth. It is accounted by CML-IA (CML-EP, measured using [kg PO_4-eq]); ReCiPe, that splits the contributions to freshwater (Re-FEU in [kg P-eq]) and marine (Re-MEU in [kg N-eq]) compartments; TRACI, which accounts for nitrogen only (TR-EU in [kg N-eq]); and ILCD, which shows three separate contributions towards freshwater (ILCD-FEU in [kg P-eq]), marine water (ILCD-MEU in [kg N-eq]) and land (ILCD-TEU in [kg N-eq]).

Table 2
Main FUs defined per vessel category.

Vessel type	CPC code	Number of publications	FUs
Cruise and Ferry Boats	49311	8	2400 passengers transported a day (Tchertchian et al., 2013, 2016)
			The vessel construction, maintenance, operation and disposal over the lifetime of 25 years (Blanco-Davis and Zhou, 2014)
			Transportation of 60 passengers and 20 bikes for 30 years (Pommier et al., 2016)
			The construction, operation, maintenance, and scrapping of alternative propulsion systems for ferry in a life span of 30 years (Jeong et al., 2018; Wang et al., 2018a)[a]
			The construction, operation, maintenance, and scrapping of a short route ferry in a life span of 30 years (Wang et al., 2018b)
			One ship during its lifetime (Cucinotta et al., 2021)
Tankers	49312	6	One average year of ship transport service (Kjær et al., 2015)
			The construction, maintenance, operation and the disposal of a tanker for a period of 25 years (Chatzinikolaou and Ventikos, 2015)
			moving one tonne of crude oil over a 1 km distance (mg-CO2/t-km) (Nian and Yuan, 2017)
			The transportation of 1 tonne of cargo for 1 km (Bicer and Dincer, 2018a, 2018b)[b]
			One oil tanker with a deadweight of 74,296 tons for the transportation of crude oil by sea over its 25-year lifetime (Quang et al., 2021)
LNG carriers	49313	1	a system capable of re-liquefying 4000 kg of the BOG (Boil Off Gas) in an hour for 25 years (Park et al., 2020)
Cargo vessel	49314	12	The transport of one ton of bulk cargo over a distance of one km by sea during T years of service (20 or 30 years) (Gratsos et al., 2010)
			The operation of the hybrid power system implemented on-board a RoRo cargo ship travelling on regular routes within ECAs over a lifespan of 30 years (Ling-Chin and Roskilly, 2016a, 2016b)
			Operation of the power system for the same RoRo cargo ship travelling on regular routes over 30 years (Ling-Chin and Roskilly, 2016c)
			Two hulls used for a duration of 26 years each (Gilbert et al., 2017)
			The transportation of 1 tonne of cargo for 1 km (Bicer and Dincer, 2018a, 2018b)[b]
			The manufacturing, 30-year operation and disposal of a ship engine coupled with a CCS system on a bulk carrier (Wang and Zhou, 2018)
			The construction of one Panamax bulk carrier for the transportation of coal from Australia to Japan over a 25-year life cycle (Tuan and Wei, 2019)
			The transport of one ton of bulk cargo over one km by sea over a 20-year service life (Dong and Cai, 2019, 2020; Quang et al., 2020)
Fishing vessels	49315	5	1 ton of landed round fish/landed seafood in one year of operation (Abdou et al., 2018, 2020; González-García et al., 2015; Ramos et al., 2011; Ziegler et al., 2018)
Tug boats	49316	2	Engine construction, operation, maintenance and scrapping (Jeong et al., 2018)[a]
			Tugboat ship performance during its service (Wang et al., 2020)
Pleasure and sporting boats	494	6	One high-speed patrol craft (TTRB-2000) hull during 25 years of service (Burman et al., 2014)
			The hull manufacturing and usage for 25 years of service (Cucinotta et al., 2017)
			The maritime operational activities and the transportation of persons and goods by sea for a period of 20 years (Favi et al., 2017)
			The construction and the disposal of a vessel for the transportation of persons and goods and/or operational activities by sea for a period of T years (Favi et al., 2018a, 2018b)
			the complete life cycle of 11 m long GRP boat hull; produced in Izmir (Turkey), excluding operation stage of the boat and recycled in a Turkish state-of-the-art recycling system (Önal and Neşer, 2018)
Others		10	FUs not provided or not clearly defined within the paper

[a] *The publication of* Jeong et al. (2018) *developed two case studies (a ferry and a tugboat).*
[b] The publications of Bicer and Dincer (2018b, 2018a) deal with several vessel categories (tankers and cargo vessels).

- Human Toxicity Potential (HTP): covers a pollutant's intrinsic toxicity as well as its dosage when it is discharged into water, air, or soil. It is measured in kilograms of 1,4-dichlorobenzene equivalents [kg1,4-DCB-eq] for CML-IA (CML-HTP) and ReCiPe (Re-HTP), while ILCD and TRACI split the toxicity contribution between carcinogenic effects (ILCD-HCE in CTUh and TR-HCE in [kg benzene-eq]) and non-carcinogenic effects (ILCD-HNCE in [CTUh] and TR-HNCE in [kg toluene-eq]).
- Ionising Radiation (IR): is concerned with the harm to human health and ecosystems caused by radioactive emissions throughout a product. It is comprised within ReCiPe (Re-IR in [kBqU235-eq]) and ILCD (ILCD-IR in [kg U235-eq])
- Land Occupation Potential (LOP)/Natural Land Transformation (NLT)/Land Use (LU): deals with the land area required during the life cycle of the product. CML-IA measures CML-LOP in [m^2yr], ReCiPe (Re-NLT) in [m^2], ILCD (ILCD-LU) in [points].
- Ozone Depletion Potential (ODP): indicates the potential for chlorinated and brominated substances to damage the stratospheric ozone layer, increasing the quantity of damaging UV radiation impacting the earth's surface. ODP is expressed in [kg CFC-11-eq] by CML-IA (CML-ODP), ReCiPe (Re-ODP), TRACI (TR-ODP) and ILCD (ILCD-ODP).
- Particulate Matter Formation Potential (PMFP)/Particulate Matter (PM)/Respiratory Effect (RE): particulate matter is a complex combination of minuscule particles. Acids (such as nitrates and sulphates), organic compounds, metals, and soil or dust particles are all possible components of particle pollution. Particle pollution is connected to plenty of health issues, including respiratory issues. It is measured in [PM_{10}-eq], *i.e.,* particles with a size of 10 μm, by ReCiPe (Re-PMFP), in [$PM_{2.5}$-eq], *i.e.,* particles with a size of 2.5 μm, by TRACI (TR-RE) and ILCD (ILCD-PM). ILCD also employs ILCD-RE, which is measured in [disease incidence].
- Photochemical Oxidant Formation Potential (POFP)/Photochemical Ozone Creation Potential (POCP)/Smog (S): highlights the detrimental effects of chemicals generated in the troposphere as a result of sunlight reacting with particular reactive substances derived from fossil fuel emissions. Photochemical oxidants are especially hazardous to human health and the environment. CML-IA expresses CML-POCP in [kg ethylene (C_2H_4)-eq], ReCiPe and ILCD make use of [kg NMVOC-eq], *i.e.*, Non-Methane Volatile Organic Compounds, for measuring Re-POFP and ILCD-POCP, respectively, and TRACI employs [g NOx-eq] for TR-S.
- Water Use Depletion (WUD): represents the usage of water resources and it is expressed in [kg H_2O] by ILCD (ILCD-WUD).

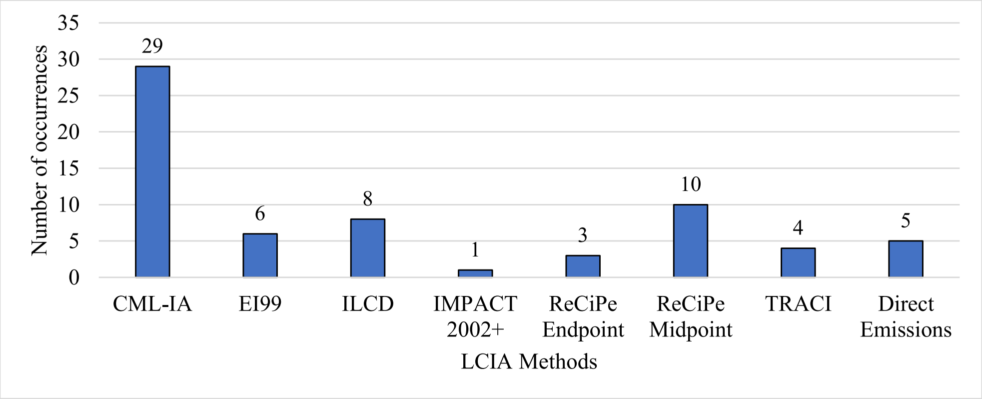

Fig. 5. LCIA methods used in the papers under investigation.

The number of occurrences of each impact category among the documents under investigation is shown in Fig. 6.

As shown in Fig. 6, identifying a suitable set of indicators that are more representative for this field is quite challenging, especially given the complexity of the system (product and processes) under analysis. The main LCIA methods used in this sector are not focused on a single-issue. In some cases, when single-issue LCIA methods were adopted (*e.g.*, CED), they were not the only LCIA method used in the analysis. Indeed, other indicators from other LCIA methods were also employed to gain a wider overview of the environmental burdens. CML-IA and ReCiPe were the most adopted midpoint LCIA methods, even though in some cases, for the sake of brevity, only a few indicators were presented in the analysis, and among them, the most used were CC/GWP, AP, EP, POFP/POCP, ETP, HTP, and ADE/RDE/MD. The CC/GWP indicator was the most commonly used since the use phase was recognized as the most impactful activity within the lifecycle of the vessel, and the combustion of fossil fuels during the operational phase has a strong correlation with the CO_2 emissions and CC/GWP indicator. Nevertheless, researchers always mentioned the need of evaluating various indicators, which are equally important and necessary to have a clear overview of the product system under investigation. The selection of a specific LCIA method is critical for standardizing LCA outcomes depending on vessel categories, bearing in mind that some specific environmental impacts can be assessed with different LCIA methods and final results may be comparable even when the calculation has been performed using a different methodology. This is the case, for instance, of CC/GWP indicators.

4.3. Background data e software tools

The data required to generate the life cycle inventories of the product systems under study have been retrieved from various sources and can be classified as specific (or primary) data and background (or secondary) data. The former are data gathered from the manufacturing facilities (*e.g.*, shipyards) where product-specific procedures are carried out, or from other life cycle activities that may be traced back to the unique system under examination (*e.g.,* peculiar operational profile, measured fuel consumption, maritime-specific operations, etc.). The latter are often generic data from widely available data sources (*e.g.,* commercial or free databases). Among the available sources, ecoinvent is the most commonly used (24 documents), followed by GaBi (14), as shown in Fig. 7. In several publications, more than one database has been adopted.

According to the review analysis, commercial databases (such as ecoinvent and GaBi) offer a good way to speed up the collection of secondary data inventories in this complex field. LCI step is very time-consuming and the adoption of commercial databases for secondary data is extremely helpful for life cycle vessel analyses. On the other

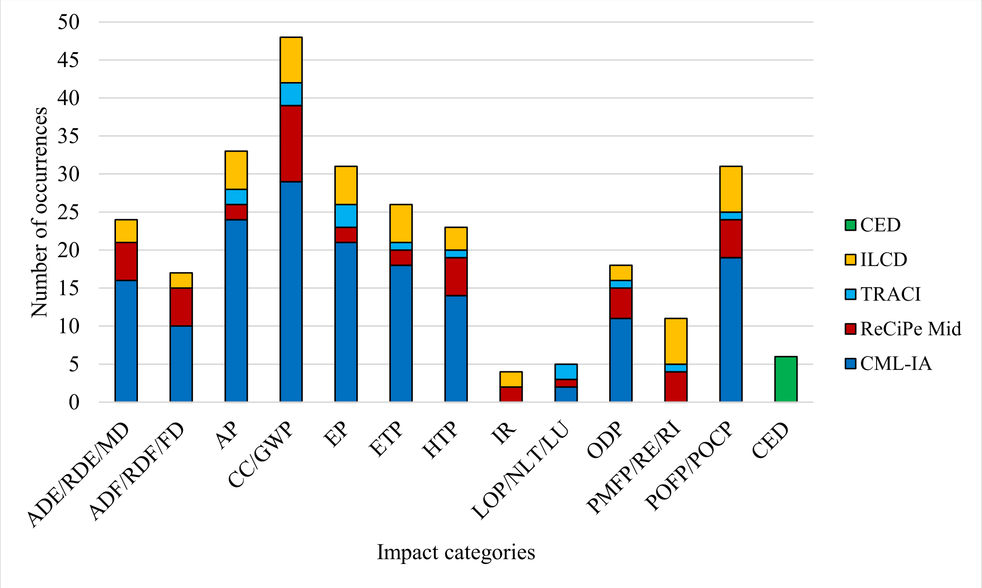

Fig. 6. Number of occurrences of the impact categories used in the documents under study.

hand, primary data from shipbuilding are necessary to reduce the variability and the uncertainty related to the construction phase (*e.g.,* the kind and quantity of raw materials employed, manufacturing processes alternatives, etc.) and to enhance the comparability of analyses performed by different researchers. The fact that the shipbuilding phase of a vessel may involve a variety of shipbuilding activities and systems (such as hulls, superstructure, power systems, equipment, fittings, etc.), each of which may vary in size depending on the specific vessel, is another essential factor to emphasize when working with primary data. These inequalities prevent a fair comparison among various studies and vessels and it would be complex to identify good manufacturing practices, as long as a normalization of the result on a common ground is not pursued.

Typically, well-established databases are provided along with commercial tools, allowing for the quick implementation of life cycle inventory and the easy retrieval of characterisation factors for a wide range of impact categories. SimaPro is the most often utilized commercial tool (20 occurrences), followed by GaBi (16 contributions). Some specific tools have been developed, accounting for 6 occurrences, while the others have not disclosed the tool used. Fig. 8 shows the software usage among the documents, where several publications employed more than one software.

Concerning the software tools used for the LCIA calculation, there are no significant differences related to the usage of a specific tool. This outcome is important in the spirit of the LCA normalization process and it suggests focusing on the type of data (both primary and secondary) and the data quality rather than the tool used for the analysis.

5. Conclusion

In this review, the authors have reported an analysis of the literature dealing with LCA studies applied to the naval sector. A number of keywords were selected and used in the Scopus literature search. The authors further refined the research findings based on the system boundary of the product system investigated by each paper, distinguishing between two major trends: (i) a system boundary that encompasses at least one vessel component, and (ii) a system boundary that only includes the fuel supply chain used in the naval sectors. Only full articles and conference proceedings from peer-reviewed journals were evaluated, resulting in 47 publications covering various categories of naval production, limited to product systems whose system boundaries include at least one component of the vessel. The main features of the bibliographic analysis outcomes have been analysed first, identifying the number of publications per year and per source, the authorships, and the country co-occurrence to better understand the trends and localization of LCA research in the maritime sector. The main trends in the published articles were then also presented, aiming to determine whether any LCIA methodology, background database, or software tool was more frequently used in the publications under investigation.

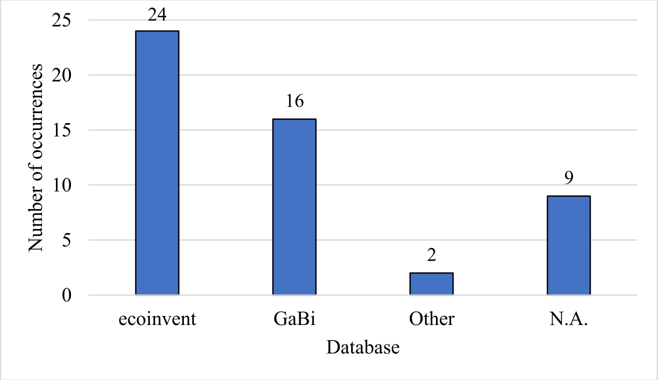

Fig. 7. Background Data sources.

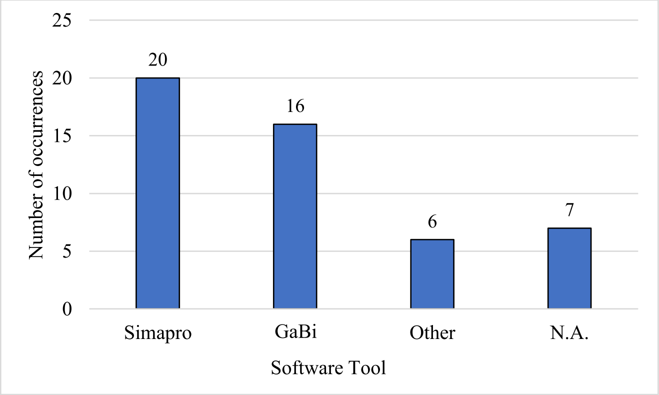

Fig. 8. Software tools used for LCA calculations in the documents under investigation.

By following this approach, a set of guidelines were defined with the aim to create an LCA normalization framework in the naval field. The establishment of a suitable allocation model is the first recommendation, as a result of the literature review the adoption of the “Allocation Cut-off” model is suggested. Another relevant aspect to consider is the definition of the FU, which should be vessel lifetime-independent to allow for a fair comparison between vessels with different lifetimes. Moreover, in the definition of the FU, the vessel category plays an important role in defining the purpose of the operational activities. Thus, the FU shall be defined following the scope/purpose of the vessel (*e.g.,* 1 ton of bulk cargo over one km transported by sea for cargo vessels). This classification is a key feature for ensuring a fair comparison among alternative solutions within the same vessel category, allowing for the identification of the main sources of environmental burdens based on the intrinsic function of the analysed vessel. Furthermore, system boundaries need to be precisely defined, indicating which life cycle phases are taken into account and which ones are ignored. The outcomes of the literature review support the splitting of the life cycle impacts of maritime vessels into specific contributions, such as “raw materials and shipbuilding”, “operation”, “maintenance”, and “end-of-life”. It is essential to report both the life cycle inventory and the outcomes of life cycle impact assessment for each life cycle phase included within the system boundary. For instance, considering the materials and manufacturing phase, practitioners shall define the modules and components included in the assessment (*e.g.,* hull, propulsion system, superstructure, etc.), preferably indicating the specific mass of each material within every component. The literature review did not clearly identify the LCIA method that is most appropriate for the naval field in terms of impact categories. In order to avoid the burden-shifting effect, a set of indicators showing potential damages in different ecosystems rather than the single-issue LCIA methods shall be used. This is the case of CML-IA or ReCiPe methods, which are the most commonly used LCIA methods in the analysed publications. On the other hand, the use of secondary data from commercial LCA database is necessary due to the large amount of data to collect and manage during the LCI phase. Commercial databases, such as ecoinvent or GaBi, are frequently used in this context. Finally, despite the occasional use of self-developed tools, the last recommendation involves the use of well-established software tools, which is a standard practice when performing LCA analyses. Nonetheless, there is no evidence that the calculation tool has any effect on the final LCA result.

These general guidelines allow for the establishment of a suitable normalization framework for the outcomes of LCA analyses in the naval field, which is described in details in the second part of this review (Mio et al., 2022). The normalization procedure enables LCA practitioners to generate consistent outcomes when assessing the environmental impact of maritime vessels. More specifically, it enables fair comparisons of ships among various vessel categories (“horizontal” normalization) and within particular groups of vessels (“vertical” normalization), supporting the decision-making process towards more sustainable engineering and design solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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