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A systematic literature review on holistic lifecycle assessments as a basis to create a standard in maritime industry

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Colors should be used for figures in print and on the Web.

Abstract

Purpose: Recent decades have seen the emergence of environmental problems such as global warming, partly caused by maritime transport. To tackle environmental problems, the shipping industry has introduced regulations, and, in response, environmental analyses have been carried out. Studies have suggested the use of life cycle assessment (LCA) in the maritime context, but due to the inherent complexity of the products studied, they mainly focus on specific phases of the life cycle, in particular the operational phase. In addition, various modelling assumptions have been used. Hence, result's reliability can be questioned and a standard to perform LCA in maritime industry could be benefic.

This article analyses current LCA methodological trends in the maritime sector and aims to be a basis of discussion for a future standard suggestion and answers the research question: How have holistic LCA studies been conducted this far and what could be done so the methodological trends meet European standards? We undertook a systematic literature review to answer this question.

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Methods: From a sample of around 1,400 articles

the systematic review combined with the snowball method identified 32 articles, on which a bibliometric analysis was carried out. Next, key LCA themes were selected for analysis: definition of the functional unit, boundary selection, cut-off rules, approach to the life cycle inventory method, impact categories, databases, life cycle inventory modelling framework, LCA tool, characterisation method, temporal and spatial aspects, normalization, weighting, uncertainty and sensitivity analyses.

Results and discussion:

Currently, most of the studies focus on data collection, and methodological shortcomings have been identified concerning 11 key LCA topics. For example, functional units were incomplete in 90% of cases; no consistency was found across boundaries; the studies present a multi-criteria approach in 85% of cases; EcoInvent (28%) and Gabi (28%) are mainly used as databases, Gabi (32%) and SimaPro (21%) as LCA software. The studies cannot therefore be compared. In addition, this highlights the limits of the reliability of the studies, which are still reliable to a certain extent.

Conclusion: For each theme, recommendations in line with the standards of the International Life Cycle Data System (ILCD) have been formulated in order to improve future studies. Future comprehensive studies should be carried out to make proposals on specific LCA methodological topics. In addition, efforts should be made to develop public databases, spatial and temporal characterisation factors, life cycle scenarios and public LCA tools adapted to the maritime context.

Keywords: LCA, LCI, LCIA, Uncertainty analysis, Shipping, Boats.

Nomenclature

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2		
3	FU	Functional unit
4	GHG	Greenhouse gases
5	GT	Gross tonnage
6	GWP	Global warming potential
7	HVAC	Heating/ventilation/and air conditioning
8	ILCD	International Life Cycle Data System
9	IMO	International Maritime Organisation
10	LCA	Lifecycle assessment
11	LCI	Lifecycle inventory
12	LCIA	Lifecycle impact assessment
13	MARPOL	Marine pollution
14	OAT	One at time
15	PEF	Product environmental footprint
16	PTW	Pump to wake
17	WTP	Well to pump
18	WTW	Well to wake
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1 Introduction

1.1 Context

The past few decades have seen the emergence of environmental issues such as global warming. These issues have brought socio-economic pressures and threats to biodiversity. Global warming is acknowledged to be caused by human activities notably in construction, agriculture, industry, and transport (Arias et al., 2021). Regarding transport, 90 % of cargo are carried by boats (The international council on clean transportation, 2007). Maritime sector is responsible for approximately 5 % of greenhouse gases' (GHG) share emitted in Europe (European commission, 2021). Furthermore, maritime transport is intended to strongly grow by 2050 (European commission, 2021).

Maritime sector has adopted global regulations in 2011 via an amendment to Appendix VI of the Marine Pollution (MARPOL) Convention, making Energy Efficiency Design Index for new ships mandatory and the Ship Energy Efficiency Management Plan mandatory for all ships (Marine Environment Protection Committee, 2011a). In 2018, to meet the Paris Agreements commitments fixed in 2015 (United Nations, 2015), the International Maritime Organisation (IMO) also created a roadmap for halving international shipping's annual greenhouse gas (GHG) emissions by at least 50 % by 2050 compared with the level in 2008 (Joung et al., 2020).

In 2015, the European Parliament passed a regulation (EU 2015/57). It requires vessels calling at European ports to measure their greenhouse gas emissions if they weigh more than 5000 gross tonnage (GT), and their main function is passenger transport or shipping (Council of the european union and European parliament, 2015). Boats that would not comply with this regulation would undergo penalties set by each country.

Other areas of environmental protection have also been tackled by the IMO:

- In 2011, the IMO published recommendations for the management of biofouling ("the accumulation of aquatic organisms such as micro-organisms, plants, and animals on surfaces

1 and structures immersed in or exposed to the aquatic environment” (Marine Environment
2 Protection Committee, 2011b)). Aimed at reducing the introduction of exotic species, these
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4 recommendations concern the owners of recreational craft less than 24 meters long (Marine
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6 Environment Protection Committee, 2011b).
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9 • In 2012, regulations were introduced to reduce noise on board ships and protect crew member
10 from noise. Concerning underwater noise, the IMO published guidelines concerning this topic
11 in 2014. These focus on the primary sources of noise such as propellers, hull form, and on-
12 board machinery. Because there were acknowledged to be knowledge gaps, these guidelines
13 were reviewed and updated in 2022 (Marine Stewardship Council, 2012).
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- 16 • In 2017, the International Convention for the Control and Management of Ships' Ballast Water
17 and Sediments, adopted in 2004, came into force worldwide for all types of ships. This
18 convention aims to prevent the spread of harmful aquatic organisms from one region to
19 another, transiting in ballast water, by establishing standards and procedures for the
20 management and control of ships' ballast water and sediments (International Maritime
21 Organization, 2004).
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- 24 • In 2020 a decrease in the sulphur content of fuel oil used onboards ships was added to
25 MARPOL Annex VI. The sulphur cap was therefore reduced from 3.5 % mass by mass (m/m) to
26 0.5 % m/m (Marine Environmental Protection Committee, 2019).
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43 Other environmental areas are now regulated as well, such as resource availability:
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- 45 • The EU Ship Recycling Convention came into force in December 2013. This concerns all EU-
46 flagged ships, as well as ships of 500 GT or above from third countries calling at a European
47 harbour or anchorage (European Parliament and Council of the European Union, 2013). It aims
48 to reduce the negative impacts linked to the recycling of ships by ensuring that proper vessel
49 dismantling methods are used to achieve safe disposal or recycling of all ship components,
50 including hazardous materials. This convention follows the Hong Kong convention which aims
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1 to ensure that when ships are recycled, after reaching the end of their operational lives, they
2 do not pose any unnecessary risk either to human health and safety or to the environment
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4 (International Maritime Organization, 2009). The Hong Kong Convention came into force in
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6 2011 and concerns all ships;
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9 • In France, recreational and competitive vessels have been covered by the Extended Producer
10 Responsibility scheme since 2019 (Ministère de l'environnement de l'énergie et de la mer en
11 charge des relations internationales sur le climat, 2016). This is based on the *polluter pays*
12 principle.
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19 There is therefore a plethora of regulations, but no general framework covering all types of vessels, all
20 life cycle phases (construction, operation, maintenance, end of life) and all environmental issues
21 (resources, biodiversity, climate change, human health).
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24 1.2 State of the art

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27 Blanco Davis et al., recently showed that life cycle assessment (LCA) can complement the IMO's
28 various regulatory measures (Blanco-Davis and Zhou, 2016). We can therefore assume that this tool
29 could also usefully accompany other regulations.
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38 LCA is a quantification method that can be used for example in a decision or an ecodesign
39 process. Ecodesign is usually used by companies to differentiate from competitors to earn
40 market shares or communicate environmental results. LCA allows assessing the environmental impacts
41 of products and services from cradle to grave (Finnveden et al., 2009). LCA is the only environmental
42 quantification method that is normalized. The two guidelines ISO14040 (ISO, 2006a) and
43 ISO14044 (ISO, 2006b) define how to process when performing an LCA. There are two
44 European guides to implementing the ISO standards: the handbook of the *International Life Cycle Data*
45 *System* (ILCD) which was implemented in 2010 (European commission, 2010) and the Product
46 Environmental Footprint (PEF) guide which aimed to supplement ILCD guidelines in 2012 (EC-JRC,
47 2012) and that has been updated in 2019 (Zampori and Pant, 2019). Even if there remain some
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challenges to develop implementation of PEF (Pedersen and Remmen, 2022), these two guides remain references in the domain.

The first step is goal and scope definition, developing all the hypotheses relevant to the assessment, such as the objectives, functional unit (FU), scope, allocation procedures, and cut-off rules. LCA is goal dependent, which means all the methodology steps are justified by goals determined in first place. Different goals might be targeted: identification of hot-spots; comparison of options for design improvement; correlation, uncertainty and sensitivity analysis; benchmarking; spatial distribution; temporal distribution (Hollberg et al., 2021).

The second step is the life cycle inventory (LCI), where all the elementary flows relative to the product are quantified from engineering data (energy, waste, co-products flows) which are called intermediate flows. If a flow carries a financial value, it is considered as a co-product (e.g., a flow that is recycled and used in a system process is considered as a co-product, whereas a flow that is intended to be landfilled is a waste). This phase is the most effort intensive. The conversion from intermediate to elementary flows is done with the help of environmental databases.

The third step is the life cycle impact assessment (LCIA). In this phase, environmental indicators are characterized by characterization factors applied to elementary flows previously quantified. It is often carried out with the help of LCA software and characterization methods.

The fourth and final step is the interpretation phase, where the study's conclusions are determined and recommendations are given (e.g., using sensitivity or uncertainty checks).

The first LCA in the maritime industry was conducted back in 1997, and concerned shipping vessels (Magerholm Fet, 1997).

Since then, according to Wang et al., LCA studies are still limited inside the marine industry, because previous studies mainly focus only on quantifying impacts during the manufacturing process or the operation phase (Haibin Wang et al., 2018). Jeong et al. pinpointed that analyses remain very complex

1 and there is also a lack of specialized LCA tools for the maritime industry (Jeong et al., 2018). In
2 addition, there are some remaining data gaps. For example, Favi et al., explained that there are great
3 many uncertainties regarding ship's end of life, as precise data are still lacking (Favi et al., 2018a). End-
4 of-life technologies are nevertheless emerging technologies, which complicate flow's determination.
5 Other issues emerge when dealing with LCA in maritime industry (e.g., Chatzinikolaou and Ventikos
6 pointed out that vessels cause different environmental impacts in different geographical areas
7 (Chatzinikolaou and Ventikos, 2015a)).

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17 A vessel is indeed a complex system: it has a great many sub-systems and alternative solutions (for
18 example : hull, motorization, electrical navigation , ...), its sub-systems are interdependent (e.g., a
19 modification on hull form might affect motorization consumption), it has different mode of operations
20 (e.g., depending on navigation conditions, boat might reduce or increase its speed), it changes
21 throughout their life cycles by maintenance cycles, and it interacts with its environment (e.g., hull is in
22 direct contact with the sea) (Tchertchian et al., 2013). Usual LCA issues (e.g., FU or boundaries
23 determination) are strongly amplified by such products, compared to simpler products. This issue
24 tends to reduce results reliability

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37 Deriving reliable results is crucial
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39 for several reasons. First decisions can be made based on products comparison (e.g., benchmarking,
40 environmental management, ecodesign tasks). Moreover, as regulations are becoming more and more
41 stringent, comparing products with regards to their regulation's compliance will become compulsory.

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46 These tasks can only be done with reliable results.

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49 Furthermore, vessels are designed for different purposes, such as the transport of goods or persons,
50 defence, competition, or specialist tasks vessels (e.g., drillship, fishing boats, cable laying) and so on,
51 which makes performing a reliable LCA study even more challenging.

1 At the boat scale, Chatzinikolaou and Ventikos explained that currently there are no agreed reference
2 about the scope, system boundaries and functional unit to study on a ship and that the choice is left
3 to the practitioner (Chatzinikolaou and Ventikos, 2015b). The literature on LCA in maritime industry
4 hence focuses mainly on the operation phase (Mondello et al., 2021) or other individual lifecycle
5 phases, but few holistic approaches seem to have been suggested. Some attempts were made by Ling
6 chin et al., to develop a framework for marine photovoltaic systems (Ling-Chin et al., 2016) but to our
7 knowledge, a comprehensive LCA methodology is not yet available in maritime industry (it is a similar
8 story in other industries). Studies' results are valid only in their scope and thus their contribution the
9 scientific community is questionable (Mondello et al., 2021). Moreover, several important choices
10 (e.g., scope, FU) made during LCA regarding the reliability of results are still left the practitioner's
11 intuition and hence result's reliability can be questioned. It could be interesting to work on an LCA
12 standard for maritime purposes, but authors believe that a review of current methodological trends
13 could be useful prior this work. As far as the authors know, there are 2 reviews dealing with LCA in the
14 maritime industry, and they deal with methodological choices.

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34 Mondello et al., produced a review paper noting that the literature mainly focuses on the operation
35 phase or on individual lifecycle phases (Mondello et al., 2021). This is because the maritime regulations
36 primarily focus on these aspects (Marine Environmental Protection Committee, 2019). Furthermore,
37 authors of this article have tended to concentrate on environmental concerns coupled with economic
38 concerns.

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52 Another review recently gave recommendations on how to normalize LCA in the maritime industry
53 (Mio et al., 2022a, 2022b). Their research helps to derive reliable results, from studies already
54 performed.

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56 It is worth emphasising the importance of
57 standardizing studies results, in order to make studies reliable.

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1.3 Research focus

In conclusion, there is no review oriented only towards environmental concerns and giving recommendations on methodological aspects regarding current LCA performed in maritime industry. We hence suggest to analyse current state of the art regarding studies' LCA methodological choices set in the past decades, and to compare these trends with current European LCA guidelines so as to derive recommendations for a future standard.

Hence, This article aims to answer the following research question: How have holistic LCA studies been conducted this far and what could be done so the methodological trends meet European standards?

We undertook a systematic literature review (Grant et al., 2009) to answer this question. Our goal was to identify methodological gaps and propose ways of bridging them by indicating future avenues of

1 research. LCA results rely greatly on methodological choices chosen by the practitioner. Hence, this
2 article is focused on the methodological aspects and do not discuss LCA results, as the values
3 determined in studies are only valid to some extent. This work is intended to be a basis for future
4 research discussions aiming to [create](#)
5 [an LCA standard adapted to maritime purposes.](#)
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45 2 Methods

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48 Based on a database search, we created two articles' subsamples to answer the research question. The
49 methodology used to find the articles is illustrated in Figure 1.
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54 We also defined five exclusion criteria to filter articles regarding their relevance to the research
55 question.
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- Articles that did not exclusively deal with vessels, included those relating to fleets or regional locations are excluded;
- Articles that focused on specific life cycle steps of vessels were excluded. This included studies focusing on specific methodological aspects of LCA, or even a particular category of vessel like for example trawlers (they did not include end of life in their analysis). We also excluded articles focusing on the operational stage, and more specifically on fuel choice;
- Articles focusing on vessel parts were excluded. Studies addressing ballast water treatments, electric cables or insulation materials were excluded;
- Articles that did not use the LCA method were excluded, meaning studies focusing on underwater noise, exotic species introduction, or other impacts using different environmental tools were excluded;
- Articles that were not written in English or which had not been peer reviewed were excluded, meaning that some technical reports that could have been considered as reference reports were excluded.

Two databases were used: Web of Science and Science Direct. The following keywords were used for the search: (“Life cycle analysis”) OR (“LCA”) OR (“carbon footprint”) OR (“environmental impact”) OR (“life cycle assessment”) OR (“environmental performance”)) AND (ship* OR sail* OR boat*). We considered articles published up to August 2022.

We began by analysing the titles on criteria derived from the research question, to eliminate duplicate articles. We then analysed the abstracts and carried out an in-depth reading of the selected articles, resulting in a total of 20 articles. The so-called *snowballing method* (Wohlin, 2014) was used to find articles that might otherwise have been disregarded. This method allowed us to find 12 new articles which were added to the sample.

During our in-depth reading of articles, two sub-samples emerged: articles reporting a case study (n = 13), and articles describing a methodology and/or developing an LCA software for maritime industry (n = 19).

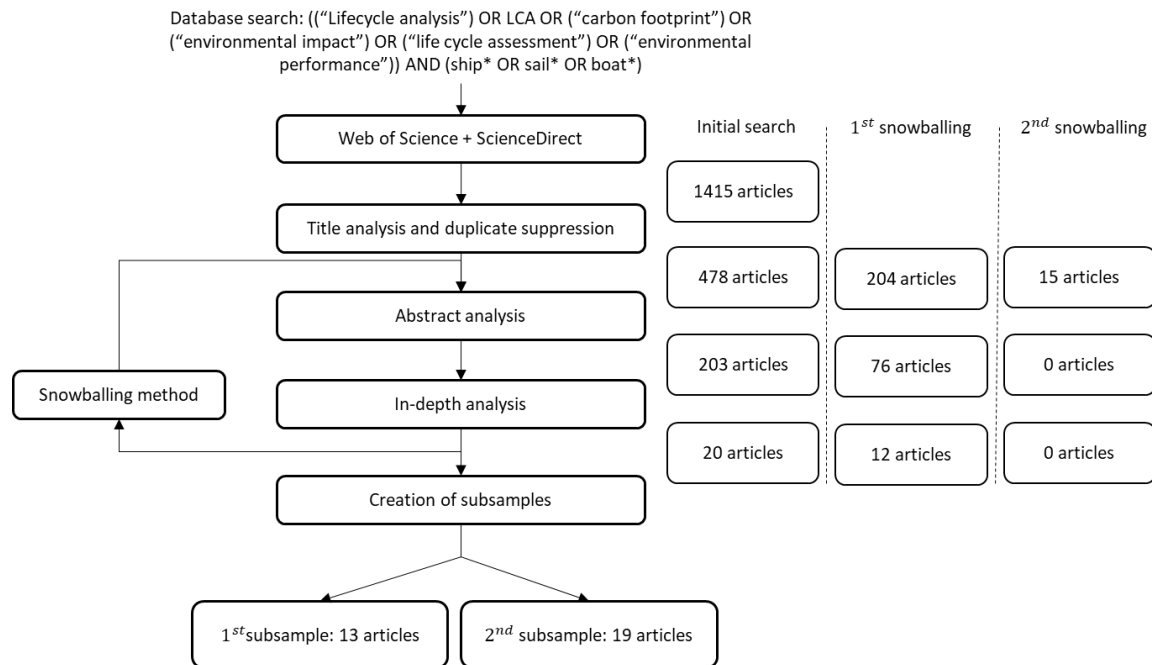


Figure 1: Article research methodology applied in the present work.

3 Global results

3.1 Bibliographic analysis

3.1.1 Geographical origins of publications

Figure 2 shows the countries where the selected articles were published. European (70 %) and Asian (28 %) countries accounted for 98 % of the articles. Locations were justified by the presence of shipbuilding (China and Greece for example) and disassembly industries (India for example). Moreover, these countries were next to major shipping lanes like for example the “tea roads” from Asia to Europe.

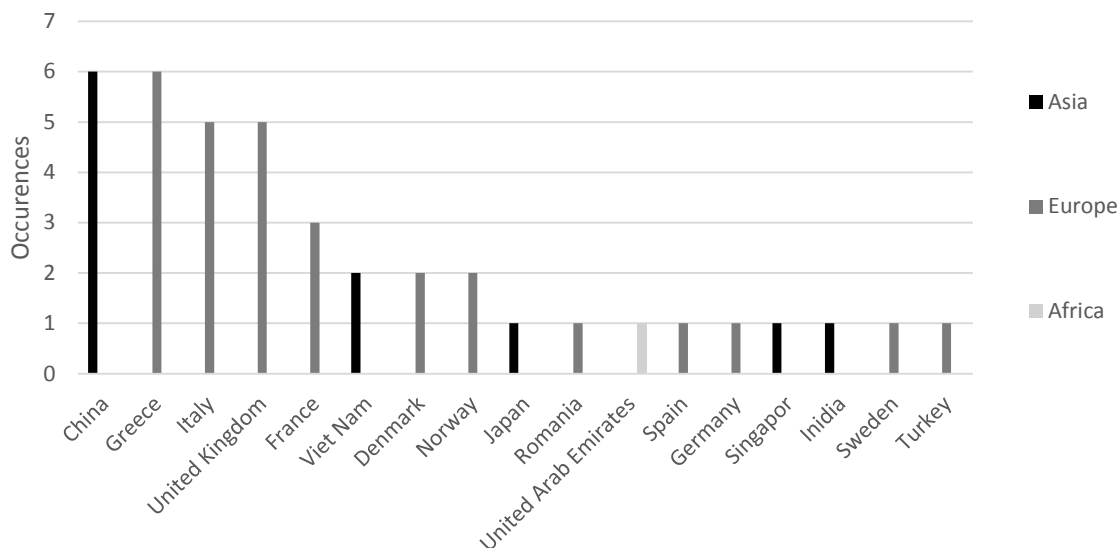


Figure 2 : Countries of publication.

3.1.2 Publication timeline

Figure 3 shows the temporal distribution of the selected articles. A growing number of articles have been published since 2014. Indeed, 72 % of the articles were published between 2014 and 2022. Few studies were published before 2014, the earliest dating from 2002.

This sudden uptick in research may be related to new regulations that were enforced the same year by IMO (Marine Environment Protection Committee, 2011a) and European Parliament (Council of the European Union and European parliament, 2015; European Parliament and Council of the European Union, 2013). Over the past few years, the industry has also shown a growing interest in environmental considerations driven by market trends (value chains and consumers).

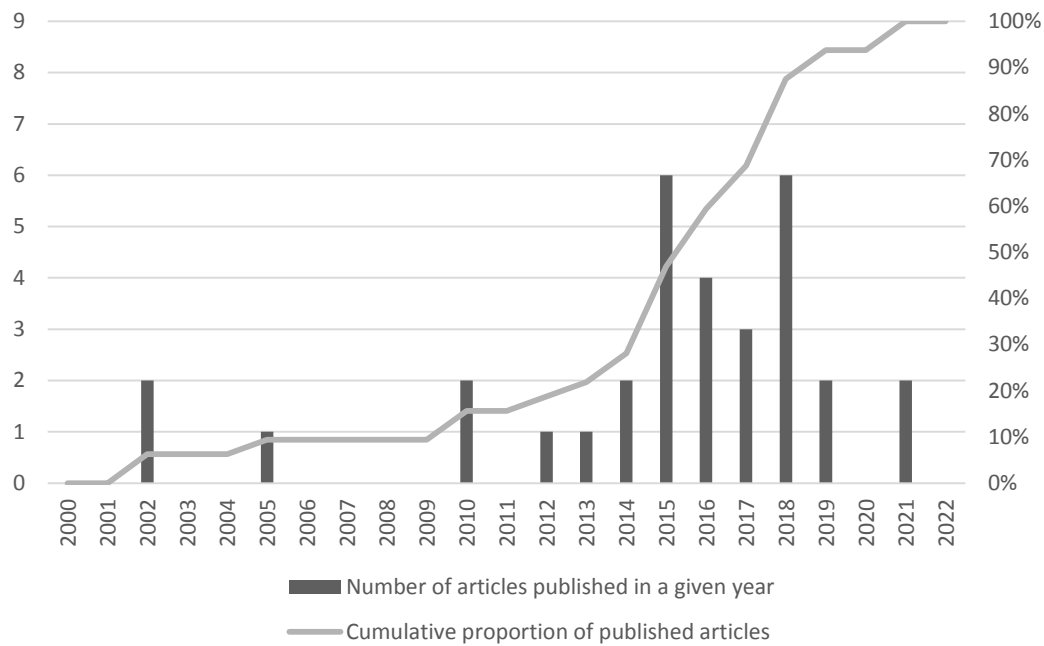


Figure 3 : Temporal distribution of selected articles and cumulative proportion of articles.

3.2 Vessel types

Four types of vessels have been mainly studied in literature: warships, passenger boats, post panamax and tankers. They represent 42 % of the vessels that were studied. This figure highlights the sheer diversity of vessel types. Vessels can be used to transport goods or people, and to defend. They can also carry out specialist tasks (e.g., for drilling or fishing), although none of the selected articles concerned this type of vessel, due to exclusion criteria set. The main function of the vessels studied in the literature is the transport of goods. . This focus can be explained by the fact that regulations mostly concern transportation. Up to now, few studies have dealt with recreational crafts.

There was considerable diversity in the shipbuilding materials in the selected articles. The latter focused mainly on steel vessels (approximately 70 %), but the warships and passenger vessels could also contain wood and composites. A composite product “consists of two or more different materials that form regions large enough to be regarded as continua and which are usually firmly bonded together at the interface” (Hashin and Pope, 1983). It can be used to reduce ship weight to reduce consumption during usage phase, but it tends to increase environmental impacts during manufacture

1 and end-of-life (Duflou et al., 2012). In maritime context we can find examples of pleasure crafts made
2 of glass fibres reinforced with polyester resins (Cucinotta et al., 2017) or carbon fibre used with vinyl
3 ester resins (Burman et al., 2016).
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6 7 3.3 General trends 8 9

10 Several key LCA topics (defined here as elements included in LCA methodology that influence studies
11 reliability) were discussed or illustrated in the selected articles, and their
12 occurrences in the sample are shown in Figure 4. Key topics are defined and explained, according to
13 ISO standards and ILCD handbook (European commission, 2010; ISO, 2006a, 2006b).
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20 The FU is the “quantified performance of a product system for use as a reference unit” (ISO, 2006b,
21 2006a), and should be determined according to the goal and decision context. It defines the function
22 that is provided in terms of quantity, duration, and quality. A reference flow can be derived from it. FU
23 is a crucial aspect of LCA, as all the study’s flow quantities are related to it. It is also worth mentioning
24 that it is impossible to compare two studies with different FUs because the whole point of LCA is to
25 compare different products serving the same function. The functional unit is a representation of the
26 function to be insured whereas the reference flow has a physical meaning, it is a quantity of products.
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37 The *system boundary* is a “set of criteria specifying which unit processes are part of a product system”
38 (ISO, 2006b, 2006a), and should be determined according to the goal, LCI modelling provisions and
39 reference flow of the study. It is in this phase that the unit processes, flows and lifecycle stages to
40 include in the study are described. A schematic system boundary diagram should also be derived. This
41 aspect strongly affects the results, in terms of reliability . Each
42 flow is responsible for environmental impacts, so neglecting any of them is tantamount neglecting
43 some study impacts.
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55 The *cut-off criteria* are the “specification of the amount of material or energy flow or the level of
56 environmental significance associated with unit processes or product system to be excluded from a
57 study” (ISO, 2006b, 2006a). These criteria are set alongside the study’s system boundary and have to
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be in line with the goal. Theoretically, no cut-off criteria should be set, but in practice, because it is difficult to have access to all the flows of the study, omissions are often made. If a cut-off criterion is to be used, it should be done by deriving physical limits to the flows of the study, regarding the percentage of impacts to be covered by the study.

In the case of multi-functional processes, several *LCI method approaches* can be used, if a partial or virtual subdivision is not possible. System substitution should be undertaken if possible. This involves substituting values from the market for the impacts of the co-function. If this is not possible, allocation procedures can be used. This step is defined as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO, 2006b, 2006a). This should be based on physical causalities as far as possible. Also, if the secondary function acts in another context system, where it only affects the existing processes’ operation, system expansion should be performed via substitution.

An *impact category* is defined as a “class representing environmental issues of concern to which life cycle inventory analysis results may be assigned” (ISO, 2006b, 2006a). It is worth mentioning that environmental impacts are different from inventory flows (which are engineering quantities). During the first step of LCA, the practitioner is supposed to select impact categories to study with respect to the study goal, and then to select an appropriate LCIA method (described here in the third step), depending on the choice of impact categories selection (which is not governed by standards). A default LCIA methodology should be time and location generic, but there is sometimes a need to differentiate between the *temporal and spatial distributions* of emissions. This topic is also discussed in the third step.

Two data categories can be found: primary and secondary data. Primary data are data relative to the company making the LCA (the foreground system). They are most of the time determined experimentally. Secondary data are data belonging to suppliers and downstream users of the

1 product/service (the background system). They are evaluated via calculations, expert estimations, or
2 documentation from grey or academic literature.
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5 When all the intermediate flows of the study have been determined, with respect to the
6 recommendations in the first step, *environmental databases* can be used to provide generic
7 elementary flows related to intermediate flows. The choice of environmental database is important,
8 as it may have representativeness issues with respect to the process to be modelled in the study, thus
9 impacting resulting values.
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12 The *LCI modelling framework* depends on the decision context. There are two approaches:
13 *attributorial* and *consequential*. When decisions made in the study may affect market trends in the
14 background system, the *consequential* approach is recommended. The consequential modelling
15 principle is a LCI modelling principle that identifies and models all the processes in the background
16 system of a system as a consequence of decisions made in the foreground system. In the case of small-
17 scale decisions, an *attributorial* approach can be used. An attributorial modelling framework is an LCI
18 modelling frame that inventories the inputs and output flows of all the processes of a system as and
19 when they occur.
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21
22 The LCA practitioner often needs to use *LCA software* to calculate the environmental impact indicators,
23 owing to flow quantities. That software can be used to perform the mandatory *classification* and
24 *characterization* steps. They can also be used to perform the optional steps of normalization, grouping
25 and weighting.
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28 *Uncertainty analysis* is defined as the “systematic procedure to quantify the uncertainty introduced in
29 the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input
30 uncertainty and data variability” (ISO, 2006b, 2006a). All the choices made in the first three steps of
31 LCA introduce uncertainty into the results. These uncertainties have to be quantified and minimized
32 to draw proper conclusions from the studies.
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Sensitivity analysis is defined as a set of “systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study” (ISO, 2006b, 2006a). It can be used alongside uncertainty analysis to evaluate study’s reliability or to find eco-design strategies.

As shown in Figure 4; key LCA topics discussed in literature are related to system boundaries, impact categories, database, LCA tool, LCIA method. Other key concepts are less represented, as functional units, cut-off rules, LCI method approach, LCI modelling framework, temporal and spatial aspects, normalization/weighting, uncertainty analyses, sensitivity analyses.

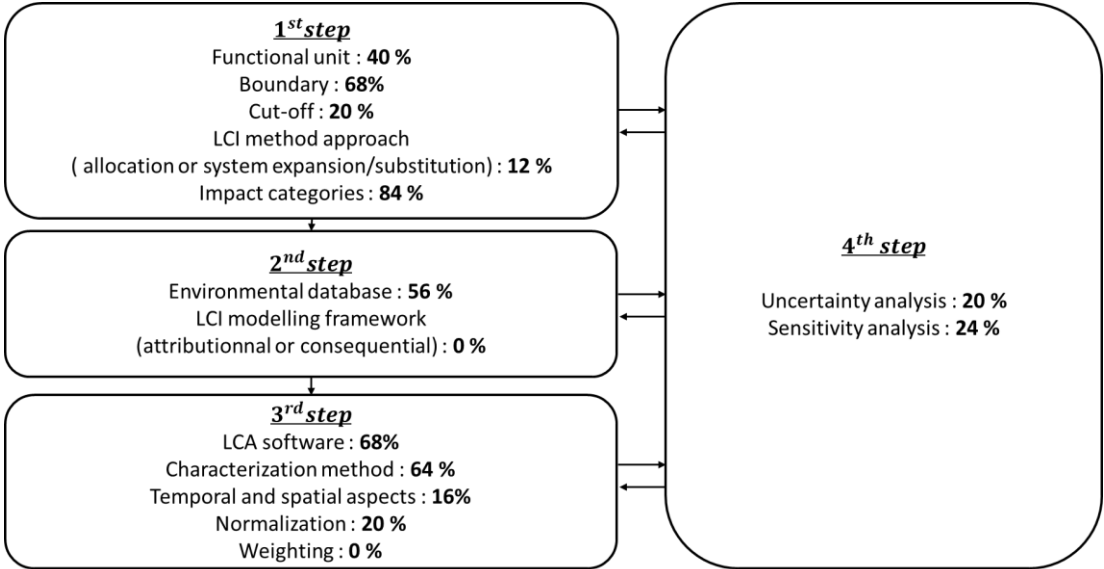


Figure 4 : Percentage of articles dealing with key LCA topics over 32 references.

4 Detailed results: Goal and scope definition

In this section, we are going to address the way LCA have been conducted so far by the selected articles in the maritime context, and analyse it in the next section.

3.44.1 Functional units and reference flows

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2
3 Table 1 gives an overview of the FUs suggested in the literature. Information completed by authors are
4 highlighted to indicate their completeness. One FU fulfils all the criteria expected to be found regarding
5 European guidelines and could be considered complete (Pommier et al., 2016). Type of vessel under
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7 study is also highlighted.
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12 Regarding function and its quantification, authors suggested that boats are likely to be used as
13 transport of goods or people for 60 % or hull cleaning. Regarding hull maintenance, the article
14 compares several scenarios of hull cleaning, taking into account the resulting overconsumptions during
15 the operational phase [44]. The question “how much?” elicited a response around 70 % of the time.
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17 The question “How?” elicited one response [39].
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25 Vessel lifetime is taken into account with various duration i.e., from the entire lifetime (25 or 30 years)
26 or to a normalized one-year value. One study suggested using a lifetime of T years [25], [47], [48]. This
27 value represents the lifespan of the product. The lifetime of the FU should correspond to the duration
28 of the function to be served.
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35 As regards to reference flows, 70 % of the time, studies evaluated the environmental impacts of a
36 single vessel, and two articles used the txkm unit. This unit represents a ton displaced over a km and
37 is often used in transport related LCA.
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43 The FUs suggested are hence incomplete 9 times over 10. According to ILCD, the questions “what?”,
44 “how much?”, “how?” and “for what duration” should be responded. Also, regarding determination
45 of reference flow to fulfil the FU, the loss of technical properties over time should be addressed, and
46 was not done in studies.
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Reference	<u>Vessel type</u>	<u>What?</u>	How much?	How?	For what duration?
(Quang et al., 2021)	<u>Oil tanker</u>	Transport	Crude oil	N.P.	25 years
(Pommier et al., 2016)	<u>Passenger boat</u>	Transport	60 passengers and 20 bikes	In continuous serve and under all weather	30 years
(Ko and Gantner, 2016)	<u>N.P.</u>	N.P.	N.P.	N.P.	25 years
(Dong and Cai, 2019)	<u>Bulk carrier</u>	Transport	1 t over 1km	N.P.	T years (20 or 30)
(Cucinotta et al., 2021)	<u>Cruise ship</u>	N.P.	N.P.	N.P.	Lifetime
(Pagoropoulos et al., 2018)	<u>Merchant vessel</u>	Hull maintenance	1 average tanker	N.P.	5 years
(Burman et al., 2016)	<u>Warship</u>	N.P.	N.P.	N.P.	25 years
(Fet, 2002)	<u>Ro-ro passenger ship</u>	Transport of passengers	555 0000 passengers, 55 000 cars, 25 000 trailers	N.P.	20 years
(Kjær et al., 2015)	<u>Tanker</u>	Transport	N.P.	N.P.	1 year
(Favi et al., 2018b, 2018a, 2017)	<u>Yacht</u>	Transport of passengers and goods	N.P.	N.P.	T years

Table 1 : functional units rised in literature.

4.2 System boundaries

Figure 5 and Figure 6 show the system boundaries set in the studies. Figures present the type of approach used, the process and flows used in it, as well as the type of data. Figure 5 presents studies where steel is the principal material, whereas Figure 6 presents other materials (composites and aluminium). It is worth mentioning that two studies included several materials:

- Burman et al., studied two types of materials: aluminium and composites (carbon fibre and glass-fibre sandwich) (Burman et al., 2016);
- Pommier et al. studied four types of materials: aluminium, exotic wood, maritime pine, and composites (fiberglass and polyester) (Pommier et al., 2016).

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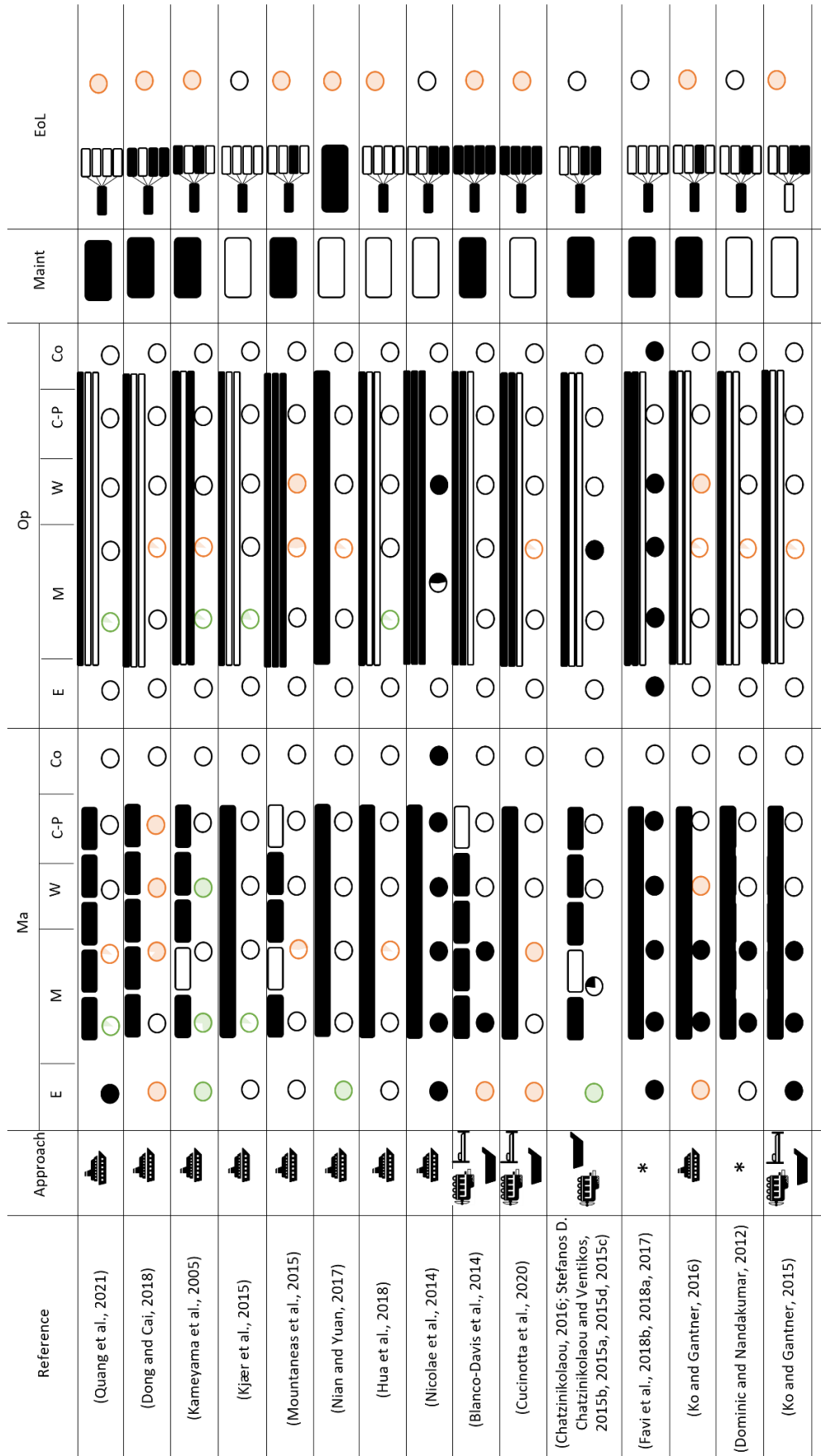


Figure 5 Boundaries used in studies with steel as principal material

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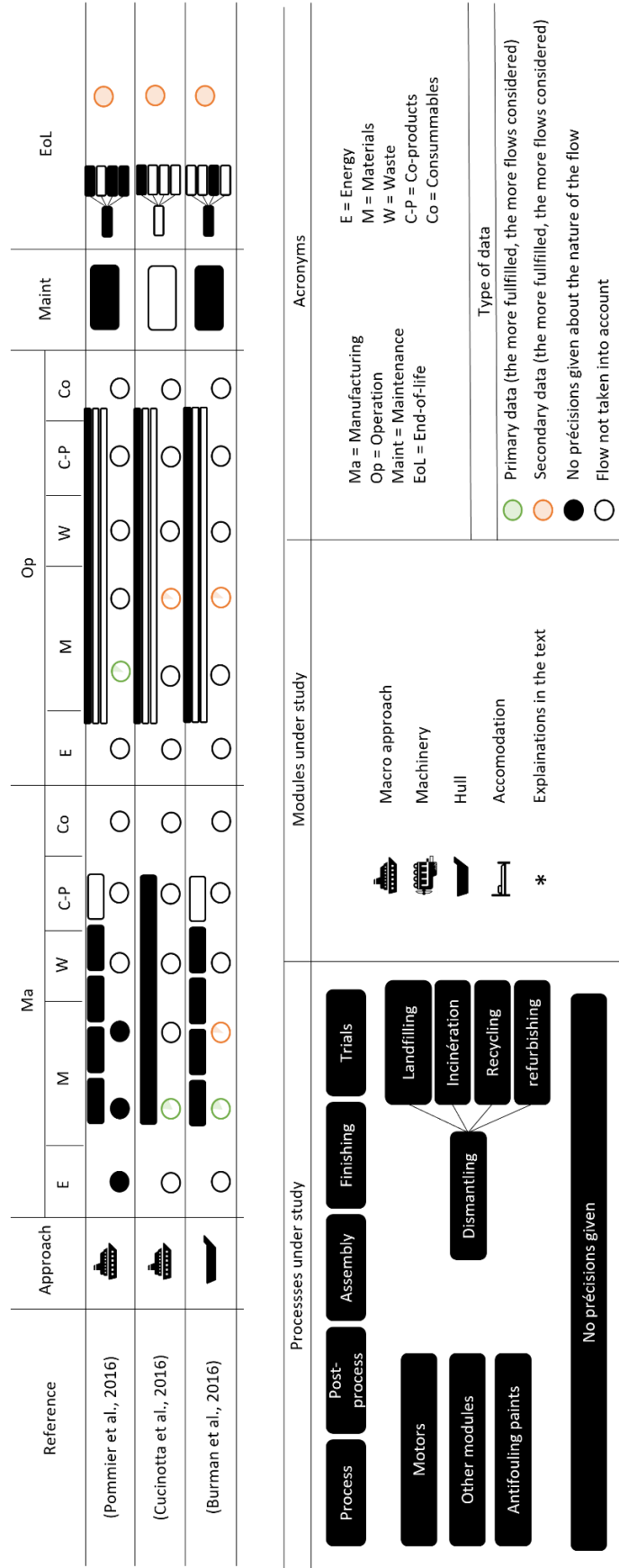


Figure 6 : Boundaries used in studies with principal materials other than steel

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When modules (way to decompose the boat), process and flows to study were not explicitly referenced, it was assumed that they were not included in the study. For the manufacturing and operational phases, process, and flows (electricity, number of materials, waste, co-products, consumables) have been addressed. When the flow is considered, the dot is filled, and the colour indicates the type of data (primary in green or secondary in red). In the case of materials, dots were filled in different proportions, depending on the number of materials under study. Dots were fulfilled in black when no information was given regarding the type of data. When no subdivision was made regarding process from a life cycle phase, a continuous rectangle is presented. Information regarding consideration of maintenance was retrieved, as process related to air emissions are the same between manufacturing and maintenance, only material quantities differ (Chatzinikolaou and Ventikos, 2015a). The scenarios considered for end-of-life was also retrieved. Moreover, even if the processes regarding the decommissioning phase are very similar to the manufacturing one, it is not possible to show the same decomposition regarding end-of-life because these details are no given transparently.

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Every article used a *cradle to grave* approach, justified by the exclusion criteria set to answer the research question (we chose to keep only holistic studies). However, there is a variety of modules, processes and flows integrated in studies. Indeed, according to Chatzinikolaou and Ventikos the choice is left to LCA practitioner (Chatzinikolaou and Ventikos, 2015c). Furthermore, two approaches were used: a *macro approach* that considered the entire vessel, and a *module approach* that considered the vessel to be made up of several modules.

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The nature of these modules varied across studies, as several different methodological choices were made:

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- Chatzinikolaou and Ventikos used a reference representation of the ship in the shipbuilding industry, whereby the system (i.e. vessel) is viewed as a series of subsystems, broken down into system elements (e.g., hull subsystem is decomposed into hull materials and hull protection as system element level) (Chatzinikolaou and Ventikos, 2015b).The authors

1 suggested that two out of eight subsystems contributed to air emissions (CO₂, CO, CH₄, NO₂,
2 NO_x, Particulate Matter, SO₂, SO_x, Volatile Organic Compounds, Non-Methane Volatile Organic
3 Compounds): the hull and the machinery.
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7 • Favi et al., identified eight functional groups, based on a literature search and functional
8 criteria: hull and superstructure, outfitting, machinery and propulsion, electrical navigation
9 and communication, piping system, Heating/ventilation/and air conditioning (HVAC),
10 accommodation and finish, painting, and insulation (Favi et al., 2018a).
11
12 • Oliveira et al., broke the vessel down into paint, propulsion, hull, and scrubber (Oliveira et al.,
13 2022).
14
15 • Cucinotta et al., Blanco Davis et al., and Ko and al., broke vessels down into hull,
16 accommodation, and main machinery. The authors justified their decision to consider only the
17 most relevant systems by citing the technical literature (Blanco-Davis et al., 2014; Cucinotta et
18 al., 2021; Ko et al., 2015).
19
20 • Dominic and Nandakumar described the vessel in terms of hull and superstructure,
21 painting/hull and deck outfitting/interior and panelling/thermal and fire insulation, machinery,
22 and electrical power distribution and lighting (Dominic and Nandakumar, 2012).
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38 Modules were suggested in relation with functional groups of the vessel, with already existing
39 standards. In the case of a complex product as a vessel, it is easier to find the principal sources of
40 impacts from the product if a module approach is taken, in opposition to the situation where a macro
41 approach is suggested (Prinçaud, 2011).
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48 For steel vessels, there seemed to be a consensus on which process to use regarding shipbuilding
49 namely cutting steel, abrasive sandblasting, welding, painting, sea trials (Quang et al., 2021). Sacrificial
50 anodes are also sometimes studied (Chatzinikolaou and Ventikos, 2015a). These processes are
51 nevertheless not always considered. Regarding composites products, authors studied materials.
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58 Electricity is not taken into account because it seems to be negligible in manufacturing processes
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(Cucinotta et al., 2017). Most of the time, waste, co-products, and consumables flows are not considered. Pommier et al., claimed that according to ISO standards, consumables flows can be neglected (Pommier et al., 2016).

It is crucial to study the operation phase, as most of air emissions and energetic resources consumptions occur at this phase (Mondello et al., 2021). Authors used scenario analysis or project documentation (deliverable of the project or monitoring reports for example) to model this phase.

Most of the time, fuel consumption is studied with several approaches (Perčić et al., 2020):

- The pump to wake (PTW) considers emissions occurring during vessel operation;
- The well to pump (WTP) considers impact related to crude oil recovery, transportation, diesel refining, and diesel distribution;
- The well to wake (WTW) approach is a combination of the PTW and WTP approach.

Nevertheless, several flows related to ballast water, anode protection, antifouling coatings, waste (sludge, bilge oil, liquid/solid oily wastes, ..) and volatile organic compounds from slop and cargo can be emitted during this phase (Mountaneas et al., 2015).

Regarding the final step of boat's life cycle, the end of life of steel vessels takes often place in Third-World countries. These vessels have a long usage time (25 to 30 years), with several actors along the supply chain. Consequently, it is unclear which end-of-life scenario to consider (decommissioning, landfilling, incineration, recycling, reusing). Hence, authors must often make choices to define the proper end-of-life processes to select

For other type of materials, such as composites, there are few data regarding end-of-life, and it is unclear which process to use (Cucinotta et al., 2017).

As a synthesis, we can say that every article used a cradle to grave approach, but following different modules decomposition. No consistency was found between boundaries, even if the principal processes regarding manufacturing seem identified. Materials are mainly studied in this phase. Fuel

consumption has been widely studied in operation phase even if other flows can create impacts.

Eventually, there is a most of the time a lack of transparency regarding the end-of-life.

According to the ILCD handbook, all the life cycle phases, processes, and flows in the technosphere (system organised by human beings) that need to be considered in relation to the FU should be included in the LCA. All deviations should be documented and recalled in the interpretation phase. A schematic view of the processes being studied should also be provided, distinguishing between the foreground and background processes, in order to make the study as transparent as possible.

4.3 Cut-off rules

Four of the articles we reviewed clearly mentioned cut-off rules:

- Cucinotta et al., used cut-off rules to select flows for inclusion in the sensitivity analysis. The sensitivity of results for items accounting for at least 10% of environmental impacts was analysed further (Cucinotta et al., 2021).
- Kjær et al., proposed a methodology based on an input-output method, which cut-off rules to be avoided, by using a *top-down* approach. From an initial financial inventory, flows of kgCO₂eq can be obtained by using specific input-output databases. This is an interesting method but it does not allow the system's components to be modelled (Kjær et al., 2015).
- (Cucinotta et al., 2021; Favi et al., 2018a) suggested using EcolInvent®'s 0:100 cut-off method for allocating end-of-life impacts to multifunctional products. This means that the producer of the waste is responsible for its impacts and environmental impacts are allocated to this latter.

According to the ILCD handbook, cut-off rules should be defined according to the system process being studied, regarding processes and flows. The flows in question are those that cross the system boundaries (waste, co-products, elementary flows). Cut-offs should be applied according to the desired accuracy of environmental impacts.

3.7.4.4 Life cycle inventory method approaches

Regarding LCI method approaches, the only ones proposed in the articles we reviewed were allocation ones, as the subdivision of processes under study were done naturally. Two articles explained their choices. (Cucinotta et al., 2021; Favi et al., 2018a) chose to allocate the impacts regarding waste flows as the producer's responsibility. This was done, as explained before, by means of cut-off procedures.

Vessels are multifunctional products. This means that the multifunctionality could be tackled at the vessel scale, as well as the process scale (co-products flows). Currently, vessel's multifunctionality is not addressed in the articles. Moreover, in the selected articles, only waste (as co-products) flows have been considered for allocation

. It might also be because co-products flows are not much considered in the studies.

According to the ILCD handbook, in the case of multifunctionality, system expansion or subdivision method should be used, depending on the decision context. Subdivision should be done based on physical criteria or virtually. If this is not possible, substitution with a market mix should be carried out, and if this is not possible, allocation should be used. In the case of allocation, physical criteria should be used, and if this is not possible, economic criteria.

4.5 Impact categories to be studied

Authors assessed elementary flows, environmental impacts, or environmental damages. Almost all the studies in the review calculated environmental impacts (91 %).

Regarding elementary flows, most of the studies assessed air emissions, owing to regulations. Several compartments of emission (water, soils, air) regarding substances emitted (CO₂, NO_x, SO_x, SO₂, CO, CH₄, N₂O, NMVOC, ...) are considered in studies.

1 Most of the articles we reviewed (85 %) adopted a multicriteria approach (six impacts assessed on
2 average), but in 15 % of the studies , only one impact was addressed: global warming potential (GWP)
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4 (Kjær et al., 2015; Ko and Gantner, 2016; Haibin Wang et al., 2018). Moreover, a list of impact
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6 occurrences in the studies is provided in Figure 7. GWP was systematically calculated, and in more than
7
8 50 % of the studies, acidification and eutrophication were also assessed. GWP was systematically
9
10 calculated for regulatory purposes. Eutrophication and acidification are both linked to the maritime
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12 world (Pommier et al., 2016), and more specifically to the exhaust products of NO_x, SO_x, and NH₃.
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14 These gases are often related to the operation phase, but other impacts are induced by other vessel's
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16 components (e.g. [ecotoxicity](#) induced by antifouling (Rossini et al., 2019)).
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22 Two relevant impacts that are addressed by maritime regulations are not covered by the studies:
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24 underwater noise (Hazelwood and Connelly, 2005) and exotic species introduction (Hanafiah et al.,
25
26 2013). Indeed, noise produced by engines might affect underwater ecosystems, but no
27
28 characterization factors can be evaluated for this impact. Also, for example, ballast water can carry
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30 micro-organisms that might become invasive when released in natural habitats different from their
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32 original one.
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36 The ILCD handbook suggests using previous studies to exclude impacts a priori of a new study.
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Environmental impact occurrences in studies

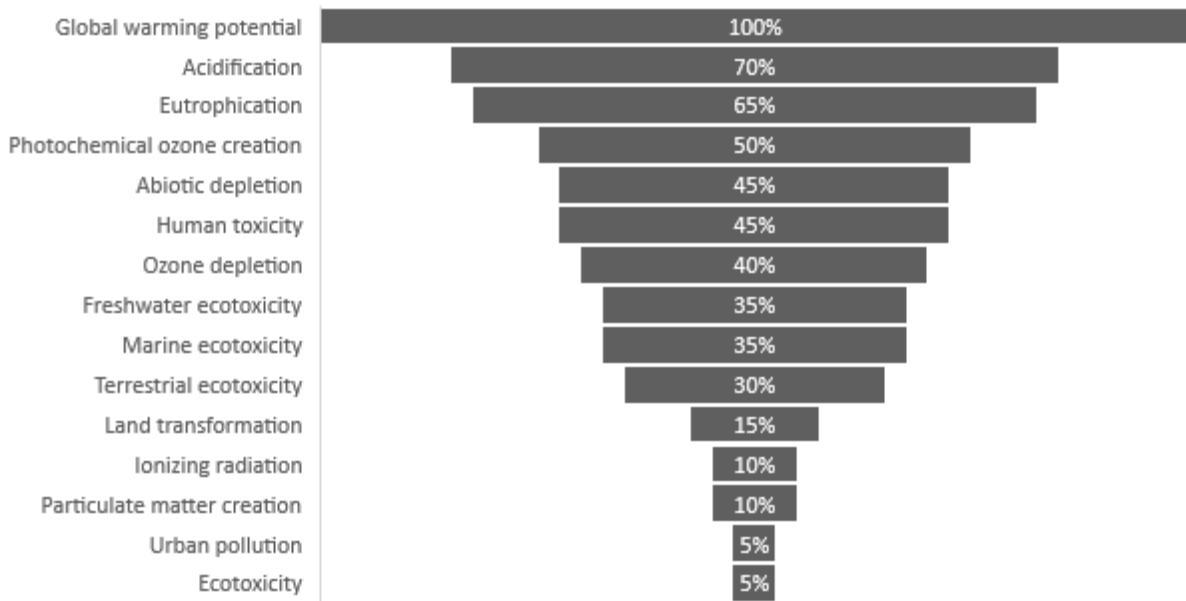


Figure 7 : Occurrences of impacts evaluated in the studies (%)

4.5 Detailed results: Life cycle inventories

Figure 5 and Figure 6 show primary or secondary data used in studies.

Regarding manufacturing, several studies determined data experimentally in the shipyard. This is the case also for operational phase, where several studies used primary data regarding fuel consumption. Vessels end their lives in Third-World countries, where data are hard to access. Consequently, most of the data about the end-of-life are secondary data.

According to the ILCD handbook, determining data experimentally should be a priority. It should permit collecting data as representative as possible with regards to the product or service under study.

4.15.1 Databases

Table 2 shows several elements related to the LCI and LCIA steps. For each study, the environmental databases, LCA software, and characterization method are indicated. Regarding environmental

1 databases, *EcoInvent* (28 %) and *GaBi* (28 %) were the most frequently used databases. Indeed, the
2 first is the most well accepted in the scientific community while the second exhibit specialized data of
3
4 interest (e.g., coating and welding materials properties or fuel consumption estimations (Haibin Wang
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6 et al., 2018)). According to Chatzinikolaou and Ventikos, generic database should be avoided, as they
7
8 are not relevant to the maritime industry (Chatzinikolaou and Ventikos, 2015a).
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12 Several authors developed internal databases, in private access. Two of them are presented section
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14 6.1. and Jeong et al., developed an internal database (Jeong et al., 2018).
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17 Also, it can be noted that among 14 different studies using databases, 6 different databases have been
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19 used.
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23 Databases selection regarding secondary data and relevance between them are crucial points, as
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25 results are not comparable if they are based on different data. The ILCD handbook recommends using
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27 secondary data that represent the case study as accurately as possible.
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30 [5.2](#) LCI modelling framework

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33 Studies used attributional approaches systematically even if they did not identify it as such.
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37 The ILCD handbook recommends using consequential approaches if the decision made in the study will
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39 potentially affect the background market. In the maritime industry, for example, this type of approach
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41 should be used if the consequences of a regulation are under scrutiny. Nevertheless, it would not have
42
43 been relevant to adopt a consequential approach within the context of this review, as the selected
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45 studies addressed issues on the scale of individual vessels.
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48 [6](#) Detailed results: Lifecycle impact assessment

49 [6.1](#) Lifecycle assessment software used

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52 Several authors have developed LCA software dedicated to maritime industry:
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- Ellingsen et al., have developed a tool mainly addressing designers that uses the GaBi database alongside primary data from shipyards (Ellingsen et al., 2002);
- Kameyama et al., have created a tool to help designers and shipyards with eco-designing. It uses data from shipyards and project documentation to produce LCIs by developing an internal database (Kameyama et al., 2005);
- Princaud et al., have developed a tool for designers with LCIs from shipyards by creating an internal database (Princaud et al., 2010);
- Koch et al., have developed a tool focusing on refit aspects that uses classic environmental databases (Koch et al., 2013);
- Tincelin et al., suggested an add-on to SimaPro software, but the latter is no longer public. This tool used EcoInvent to produce LCIs (Tincelin et al., 2010).

These software are relevant because they are mainly aimed at designers, which have the most influence on eco-design process (Jeswiet and Hauschild, 2005). They also address data availability issues by incorporating databases which provide sector-specific data. However, as they are not public, they cannot be used by companies in the maritime industry.

A variety of LCA software have been used in studies, with GaBi (32%) and SimaPro (21%) being the most popular. LCA results can differ from one software to another, owing to possible differences in the implementation of characterization factors (Aparecido et al., 2017).

Also, it can be noted that among 19 different studies presenting LCA software, 10 different ones have been used.

[6.2](#) Methods of characterization for impact evaluation

Several authors used CML method from 2001 (Brujins et al., 2002), or with characterisation factors updated in 2016 (39 %) (CML (Institute of Environmental Sciences), 2016). According to Princaud et al., this method covers a wide range of substances responsible for eutrophication and acidification

1
2 (Prinçaud et al., 2010). ReCiPe 2009 (Goedkoop et al., 2008) or 2016 (Huijbregts et al., 2016) (33 %)
3 was also frequently used on account of its reliability (Pommier et al., 2016).
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5 We analyzed 18 different articles using 12 different characterization methods.
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8 According to Hauschild et al., the choice of characterization factors should cover all the flows induced
9 by the industry (Hauschild et al., 2013). However, Chatzinikolaou and Ventikos warned that currently
10 used characterization methods do not fit the maritime context, due to a lack of temporal and spatial
11 resolution (Chatzinikolaou and Ventikos, 2015c).
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17 6.3 Spatial and temporal aspects 18

19 Three of the articles we reviewed discussed spatial and temporal aspects in the characterization step:
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- 22 • Prinçaud et al., developed a method for including both temporal and spatial aspects in the CML
23 method, but the latter is not a public method (Prinçaud et al., 2010).
24
- 25 • Pagoropoulos et al., used spatially differentiated eco-toxicity characterization factors from
26 Dong et al., (Dong et al., 2015) in their study (Pagoropoulos et al., 2018).
27
- 28 • Chatzinikolaou and Ventikos argued that determining emissions and receptions compartments
29 is challenging in the case of a ship and that characterization factors are currently oriented
30 towards terrestrial structures (Chatzinikolaou and Ventikos, 2015a).
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41 Nevertheless, spatial and temporal aspects of the method must be emphasized, regarding the fact that
42 a vessel has a long lifetime, operates in several geographical areas and induce local or regional impacts
43 (e.g., antifouling leaks are responsible for marine toxicity (Rossini et al., 2019)). Marine toxicity is a
44 local impact and might induce worse consequences depending on the route used by the boat.
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50 The ILCD handbook states that generic LCIA characterization method that are not time or location
51 dependent should be used to meet the goals defined in the first step, unless otherwise required. It
52 would therefore seem useful to assess spatially and temporally distributed impacts in the maritime
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1 industry (Chatzinikolaou and Ventikos, 2015a). According to the ILCD handbook, these aspects have to
2 be justified by comparing results from generic and non-generic methods.
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5 6.4 Normalization/weighting 6

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8 Normalization was performed in relation to different scenarios (Pagoropoulos et al., 2018; Pommier et
9 al., 2016), World 1990 values (Burman et al., 2016), or authors used CML 2001 normalization factors
10 (Cucinotta et al., 2017; Dong and Cai, 2019; Quang et al., 2021). No studies used weighting. According
11 to the ILCD handbook, normalization and weighting can be used to determine cut-off rules or help
12 interpret results, but this is an optional step. If the study is comparative and aimed at the public,
13 weighting should be avoided. The PEF guide recommends using normalization and weighting to
14 identify major impact categories, lifecycle phases, flows and processes in the study, for communication
15 purposes.
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Reference	Environmental databases	LCA software	Characterization method
(Burman et al., 2016)	N.P.	Simapro	CML2001
(Fet, 2002)	N.P.	Simapro	N.P.
(Quang et al., 2021)	GaBi	GaBi	CML2001
(Cucinotta et al., 2017)	GaBi	GaBi	CML2001
(Blanco-Davis et al., 2014)	GaBi	GaBi	CML2001
(H. Wang et al., 2018; Haibin Wang et al., 2018)	GaBi	GaBi	CML2016, ReCiPe, TRACI, ILCD
(Ko and Gantner, 2016)	GaBi	GaBi	ReCiPe, USEtox, human toxicity, on cancer
(Jang et al., 2021)	GaBi	GaBi	CML2001
(Dong and Cai, 2019)	GaBi	GaBi	CML2001
(Pagoropoulos et al., 2018)	EIO database	N.P.	Dong. Et al, 2016
(Pommier et al., 2016)	EcoInvent	Simapro	ReCiPe MidPoint (H)
(Strazza et al., 2015)	EcoInvent	Simapro	N.P.
(Cucinotta et al., 2021)	EcoInvent	OpenLCA	ILCD2018
(Dominic and Nandakumar, 2012)	N.P.	N.P.	N.P.
(Pagoropoulos et al., 2018)	N.P.	N.P.	IPCC, Dong et al., Owsianiak, 2013, USEtox
(Kameyama et al., 2005)	Internal database	Internal tool	LIME
(Prinçaud et al., 2010)	Internal database	Internal tool	CML2001
(Mountaneas et al., 2015)	N.P.	Algorithm	ReCiPe
(Nicolae et al., 2014)	N.P.	SolidWorks	N.P.
(Chatzinikolaou, 2016; Chatzinikolaou and Ventikos, 2015b, 2015a, 2015d, 2015c)	N.P.	Algorithm	Algorithme
(Kjær et al., 2015)	EIO database	SimaPro	N.P.
(Jeong et al., 2018)	Internal database	Algorithm	ReCiPe, TRACI, CML2001, CML2016
(Favi et al., 2018b, 2018a, 2017)	EcoInvent	SimaPro	ReCiPe midpoint (H)
(Hua et al., 2019)	N.P.	Algorithm	Algorithm
Number of different elements	6	10	12

Table 2: Databases, LCA tools, and characterization methods in LCA studies.

67 Detailed results: Interpretation

Figure 8 presents the different steps to perform sensitivity or uncertainty analysis, as well as mathematical tools used to perform the steps, according to (Igos, 2018). Firstly, uncertainty is characterized. Probability distributions or variance for quantifiable parameters, fuzzy sets for expert

opinions or multiple scenarios from model structure can be used. Then, the characterization can be used to perform the uncertainty propagation. This step can be done by using sampling methods (Monte Carlo for example), analytical resolution, fuzzy logic, advanced sampling, or hybrid approach). Finally, results from uncertainty characterization or analysis can be used in a sensitivity analysis to check result's reliability. Sensitivity analysis can be performed by local sensitivity analysis (OAT, OAT based on uncertainties), global sensitivity (correlation analysis, marginal analysis, MoEE, key issue analysis or Sobol analysis) (Igos, 2018). It must be noted that scenario analysis can be used to perform uncertainty or sensitivity analysis. The different method presented are to be chosen regarding the information provided, its implementation in LCA software with regards to time required to implement and reliability.

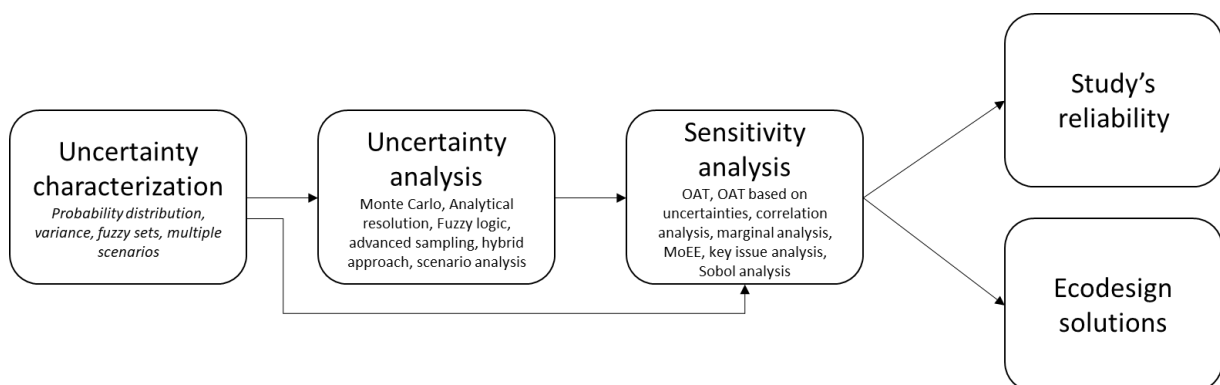


Figure 8 : Schematic view of uncertainty and sensitivity analysis

Several uncertainties sources are presented in literature regarding:

- Boundaries: Fet claimed that LCA results can be uncertain due to inconsistency in the system boundaries (Fet, 2002);
- Hypotheses: Chatzinikolaou and Ventikos stated that some parameters are crucial in order to establish correct flow quantities (e.g., engine load) (Chatzinikolaou and Ventikos, 2015a);
- Flows quantities: Tuan and Wei stated that there were uncertainties in the material and energy consumption data needed for their study (Tuan and Wei, 2019). Fet said that results uncertainties can be caused by poor data quality (Fet, 2002);

- Life cycle phases:
 - Operation: Favi et al., pointed out that the operation phase of private vessels is subject to considerable uncertainties, unlike that of public vessels (Favi et al., 2018a);
 - End-of-life: Tuan and Wei concluded that LCA for vessel's end-of-life is still complicated and uncertain, owing to uncertainties surrounding this phase (Tuan and Wei, 2019). Favi et al., highlighted a lack of regulation regarding this phase (Favi et al., 2017);
- Database reliability: Fang et al., warned that uncertainties can stem from the presence of obsolete data in the databases (Fang et al., 2020);

Normalization/weighting: Chatzinikolaou and Ventikos pointed out that these two steps are subject to the greatest uncertainties in the methodology (Chatzinikolaou and Ventikos, 2015b). Scenario characterization is used in literature to conduct uncertainty and/or sensitivity analysis. Hence the characterization is presented in this section, and it is acknowledged that it is linked to the analysis mentioned:

- Cucinotta et al., assessed three types of usage intensity for recreational sailing (Cucinotta et al., 2017).
- Wang et al., made assumptions regarding maintenance intervals (Haibin Wang et al., 2018).
- Dong and Cai developed hypothesis about the lifetime of the FU considered (Dong and Cai, 2019).
- Pagoropoulos et al., derived three types of scenarios (high, low, average) regarding the discrete events (e.g. waste treatment) (Pagoropoulos et al., 2018).

Probability distribution derived from EcoInvent database (Cucinotta et al., 2021) have also been used in literature. When using EcoInvent Pedigree matrix the practitioner evaluates reliability, completeness and temporal correlation, geographic correlation and technical correlation of the data used regarding the process considered to derive distribution law regarding flows of the process under study.

7.1 Uncertainty characterization

Two authors performed an uncertainty analysis by using Monte Carlo sampling: Cucinotta et al., quantified their results' uncertainties related to data quality (Cucinotta et al., 2021). Pagoropoulos et al., used Monte Carlo analysis to estimate the uncertainty related to their characterization methods (Pagoropoulos et al., 2018). Also, authors used scenario characterization previously mentioned to perform uncertainty analysis.

The ILCD handbook recommends quantifying uncertainties related to inventory, characterization factors, modelling choices, and hypothesis. Efforts should be made to quantify uncertainties related to each of these elements in the maritime industry.

7.2 Sensitivity analysis

In maritime industry, scenario analyses have been performed by One At Time (OAT). OAT consists in varying each input variable of the study within a particular range. In the case of OAT based on uncertainties, variables vary within their uncertainty range. Several approaches have been tested to perform sensitivity analysis using OAT:

- Dong and Cai varied their input variables by putting lower and upper limits based on the practitioner's assumptions (Dong and Cai, 2019);
- Cucinotta et al., used OAT based on uncertainties to evaluate robustness of their results, using the previously uncertainty analysis performed (Cucinotta et al., 2021);
- Pagoropoulos et al., used OAT based on uncertainties to check their result's reliability.

Even if OAT based on uncertainties depicts better the reality than OAT method, it cannot depict the correlation between input parameters and thus correlation analysis should be preferred (Igos, 2018).

8 Discussions

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In this section, methodological trends are discussed regarding their relevance to European guidelines, in order to serve as a basis to a future LCA standard.

8.1 Goal and scope

Few complete FUs were proposed in the articles we reviewed. It is important to define the magnitude, duration, and a minimum performance criterion for each of the functions fulfilled by different vessel types. The function mainly addressed is transport. Nevertheless, many other functions can be fulfilled by vessels. Transport function should moreover be divided between goods and people, so it is possible to compare different types of vessels. Hence, there should be a development to define FUs related to other functions (e.g., competition, specialized, military purpose).

FUs are often confused with reference flows, but these two are actually quite distinct. A physical reference flow should be determined for every FU. A concern is when no FU is set, studies cannot be compared, and their reliability can be questioned, favouring bad quality products, as they usually use less flows to produce products by degrading the quality. Even if some articles set functional units and a proper reference flow in txkm (for transport purposes), the criteria's variety regarding FUs proposed is still a problem for the same reasons mentioned before.

Boundaries were incomplete, and there was no consistency across studies. There was a lack of transparency, mainly related to foreground and background processes and the flows being studied. The end-of-life is always in the background processes, due to the lack of data and a low technology readiness level. These observations imply several issues:

- Differences in boundaries between studies make the results impossible to compare;
- Incomplete boundaries regarding defined FUs diminish the reliability of results;
- The use of secondary (i.e., less representative) data also reduces the reliability of results;
- The lack of transparency regarding the processes and flows being studied reduces the reliability of the studies and makes them impossible to compare.

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Currently, no common vessel's subdivision have yet been agreed. These subdivisions could be useful to compare several vessel's LCA results (in order to compare some specific vessel parts between each other in several studies) and should be based on industry standards and functional vessel groups. Moreover, a common module decomposition could help defining generic processes to use for future studies.

Few studies have set cut-off rules, but it is a good point because no complete studies have been made and cut-off rules have to be derived from complete study regarding accuracy desired on impacts quantified. Some cut-off rules were used to model end-of-life, which is a classic issue in LCA. Some authors have proposed cut-off rules, but these should be based on the desired impact coverage. Cut-off rules could then be determined based on the results from complete studies.

Boats multi-fonctionnality has never been assessed in literature. Moreover, Few allocation procedures regarding co-products (as recycled wastes) flows were undertaken in the articles we reviewed, mainly

1 because those flows are often neglected. Allocation issues will have to be discussed regarding the
2 vessel's multi-functionality and co-products flows from processes. Criteria should be based on physical
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4 aspects (e.g., mass transported or distance travelled in case of multi-fonctionnality) and if not possible,
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6 on economic aspects. A particular emphasis should be put on end-of-life process to avoid double
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8 counting or neglecting impacts due to end-of-life. This phase should be modelled accurately, and
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10 substitution points will have to be identified to apply correct allocation rules. The co-products
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12 flows allocation procedures should be modelled according to other system's rules, so no impacts are
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14 neglected between systems.
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19 There is currently no consensus on which impact categories to analyse, but most of the studies we
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21 reviewed adopted a multicriteria approach. This is expected to be quality analysis since elementary
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23 flows are not a consequence on ecosphere (system not organised by human beings) and damages bring
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25 additional uncertainties in their models. Nevertheless, studies should consider the same substances
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27 and compartments of reception/emission to evaluate comparable results. Two relevant impact
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29 categories that could also be included in the studies are underwater noise and the introduction of
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31 exotic species. However, characterization factors are not quantifiable for noise. Those two impacts
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33 should be analysed apart classical ones. A consensus should be found on which impact categories to
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35 include in studies for a given vessel type. This choice should either be based on a reference study or
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37 be made with a panel of industrialists. These propositions could help making decisions by reducing the
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39 quantity of impacts under study and focus only on representative indicators for the maritime
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41 environment.—Impacts should nevertheless be representative enough to avoid negative impact
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43 transfers.
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51 8.2 Lifecycle inventory

52 Data quality and transparency are a crucial point related to LCA results reliability. There was a lack of
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54 transparency regarding the choice of method for determining flows in the studies we reviewed.
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56 Determination methods should be specified, in order to make it easier to assess the reliability of results
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1 Primary data should be retrieved experimentally or, if not possible calculated,
2 specifying all the calculation hypotheses. Where data are retrieved experimentally, the method should
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4 also be specified. Data concerning the operation phase can be generic if the precise operational profile
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6 is unknown.
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10 Ecolnvent and GaBi are the databases that were most frequently used in the studies. Some authors
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12 had developed their own databases, but these were private, and hence not usable by others. The
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14 variety of databases used makes the studies' contributions less relevant.
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16 Moreover, no information is given regarding the methodology set to retrieve data in the databases.
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18 This degrades the reproducibility of science and data reliability. Guidelines should be drawn up on
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20 which database to use. An even better solution would be to develop a common, transparent,
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22 scientifically, and publicly accepted database for the maritime industry. Modelling rules from this
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24 database should be clearly defined. Such a database would save time and efforts to determine reliable
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26 inventories. The background processes included in the database could be informed by companies,
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28 which would provide generic inventories in order to keep their intellectual property.
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39 Even if we did not exclude consequential approaches, the modelling framework was always
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41 attributional in the studies we reviewed, and always corresponded to the decision context. This implies
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43 that some aspects like for example data and model localization, or temporal integration will not be
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45 studied by articles under study. However, if the decisions made in LCA are liable to affect the market
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47 of background processes, an attributional approach should be implemented, using system expansion.
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51 This would be the case if the consequence of a regulation were to be analysed for example.
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53 8.3 Lifecycle impact assessment

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57 Different LCA software were used in the studies we reviewed, and the studies' results depended on
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59 the choice of software. Several authors developed LCA software of their own, but these were private
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1 and hence unusable. Efforts should be made to provide a LCA software in free access dedicated to
2 maritime purpose. Studies could hence be compared across each other, and results could be reliable.
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4 Regarding this subject, “Marine Shift 360” (Marine Shift 360, 2022) is a public simplified LCA software
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6 that is intended to help promoting LCA in the maritime sector. Its structuration is ergonomic for
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8 industrials in maritime sector. Nevertheless, it is used as a *black-box* by architects and shipyards,
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10 affecting the results reliability, due to a lack of transparency.
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14 ReCiPe and CML are the most frequently used characterization methods. However, it would be
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16 interesting to develop a method for maritime purposes. In any case, some of the references used
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18 methods that are quite old now. For example (Prinçaud et al., 2010) adapted the UseTox® method but
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20 this latter has been enriched since then (Marian et al., 2017), which means that their adaptation of the
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22 method should be adapted in the actual context. This could help reduce uncertainties related to the
23
24 choice of characterization factors and enhancing studies reliability. It would be useful to
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26 develop characterization factors regarding underwater noise and exotic species introduction, as these
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28 impacts are the subject of regulation, or are mentioned to be a consequence of maritime
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30 transportation (Hanafiah et al., 2013). Moreover, a good understanding of the contexts around vessel’s
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32 lives (e.g., coasts, underwater characteristics, harbours) or about the regulations (e.g., IMO sulphur
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34 cap, Extended Producer Responsibility scheme) would help to assess a desired level of accuracy
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36 regarding maritime specific characterization factors and to choose indicators to use regarding lifecycle
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38 phases considered. This work could be a full article’s topic. For example, the human toxicity could be
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40 interesting to study during manufacturing phase, but during operation, indicators related to the
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42 maritime world seem better (e.g., eutrophication, acidification, ecotoxicity). Moreover, global
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44 warming potential could be studied in all life cycle phases.
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56 Spatial and temporal aspects were often neglected from the studies we reviewed. One author
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58 proposed to adapt the CML method to respond this goal, but its characterization factors are not public.
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7 Yet, a boat is a product that creates local impacts, has a long lifetime, and operates in different
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9 geographical areas. Hence, it could be interesting to develop characterization factors for the maritime
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11 industry that consider the spatial and temporal aspects. Databases should include spatial and temporal
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13 aspects, with special considerations to the operation phase, as
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15 it has a long lifetime and operates in several geographical locations, not always
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17 known. Generic and non-generic methods could then be compared to assess the differentiation
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19 relevance.

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22 Few studies featured a normalization and weighting step. This step adds uncertainties in addition to
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24 the ones already included in LCA method. It can be used to make interpretation easier for the
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26 practitioner but may be avoided if the LCA is being carried out for communication purposes. In the
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28 case of a standard, it would not be relevant to assess these steps.

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31 Also, regarding the number of combinations from databases, LCA software and characterization
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33 factors, studies can't be compared between each other's. This reinforces the fact that there should be
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35 a consensus in the choice of a software, database, and characterization factors to use in maritime
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37 context.

41 42 8.4 Interpretation

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45 Every key LCA topic can inject uncertainty into the results, but only uncertainties related to inventory
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47 elements, characterization factors, modelling choice, and hypotheses should be considered, according
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49 to the ILCD-~~H~~handbook.

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53 Currently in the maritime sector, probability distribution derived from EcoInvent database or from
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55 probability laws and multiple scenarios have been used to tackle uncertainty characterization issues.
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57 However, it could be interesting to use variance or fuzzy sets methods to perform this phase regarding
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time considerations to characterize uncertainty analysis to improve results and interpretation's reliability.

For the moment, scenario generation addresses usage and end of life phases mainly. Efforts should be made to provide precise life cycle scenarios regarding these phases which tend to be complex in such a product as a vessel. Those efforts could help designing better products regarding these phases by modelling uncertainties and sensitivities analysis in a better way.

Few uncertainty analyses were conducted in the studies, even though there are various sources of uncertainty in the maritime industry. When uncertainty analysis was performed, authors used Monte Carlo sampling. Efforts should be made to facilitate uncertainty analysis, in order to rise the study conclusions more reliable.

Sensitivity analyses should also be carried out. Few of the studies we reviewed included sensitivity analyses. Even though, this step can help to determine hot-spots and verify the reliability of the results relative to modeling choices. Analyses were mainly carried out using OAT or scenarios analysis. OAT methods are easy to implement, but correlation analysis should be preferred, in order to link input parameter to output parameters.

Uncertainty and sensitivity analysis were seldom conducted in the studies. Efforts should be made to quantify these aspects, in order to enhance study reliability and robustness.

8.5

Discussions to create a standard

On the basis of methodological trends found in literature, we can discuss the next steps that could be implemented to create a LCA standard in maritime industry. First, it can be stated that several methodological challenges have to be faced, based on current trends:

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- Several functions are insured by different vessel types (e.g., drilling, shipping, transporting people, competing) and FUs should be determined for different types of vessels;
 - Several flows are likely to contribute to environmental impacts and omitted of studies we reviewed. These occur in different lifecycle phases (e.g. antifouling paints occurring in operation phase, Volatile Organic Compounds during manufacturing phase) and differ depending on the type of material under study (e.g., steel, composites, copper). Complete boundaries should be defined to form the basis for future studies, and cut-off rules should be defined regarding the desired level of accuracy for impacts;
 - Allocation rules are to be set for the maritime industry. These rules will be defined for co-products flows (e.g., steel wastes recycled during manufacturing processes) and multi-functional vessels (e.g., vessels used for the transport of goods and persons) ;
 - Impact categories for studying different types of vessels should be selected based on the vessel's lifecycle context (e.g., it might be useless to study marine ecotoxicity on a steel boat which is not covered by antifouling paints, during the use phase);
 - Choice of database should be discussed, especially the degree of specificity if a database is created for the maritime industry (e.g., at present, generic recycling processes from classical databases as *EcoInvent* are not representative of end-of-life processes);
 - The LCI modelling choices need to be discussed, especially the best way of modeling the consequential approach in the maritime industry (e.g., it might be useful to study the implementation of an IMO regulation);
 - Features included in an LCA tool dedicated to the maritime industry should be addressed by the scientific community, regarding its intended audience (e.g., naval architects, shipbuilders) and the need of that audience;
 - Characterization factors should be created for maritime purposes, addressing the issues of the temporal and spatial distribution of local impacts. Factors regarding underwater noise and the introduction of exotic species could be developed;

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- Normalization and weighting steps are for the moment handled properly;
 - Strategies for handling uncertainties should also be addressed, so that sensitivity and uncertainty analysis can be performed more easily in future studies, thereby enhancing result reliability (e.g., the operational phase carries high uncertainties, so it might be useful to determine reference operational scenarios representative of different vessel types).

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To address several of these topics (e.g., cut-off criteria, impact category selection), comprehensive reference studies should be conducted to derive hypotheses regarding the first step of LCA. These studies should be transparent, so that their provisions can be used for future studies.

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Based on these research efforts, concrete open tools could be developed to help disseminate a LCA standard in the maritime industry:

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- A comprehensive, public, transparent, and reliable database should be created to help make LCA more widespread in the maritime industry. This database should include spatial and temporal dimensions, especially related to the operation phase. Data should also be generic, so companies keep their intellectual property.
 - A public and transparent LCA software should be created along the database and characterization factors to aid decision making at different lifecycle stages of a project. This software would need to adapt to user's different LCA needs. This software should have a

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module approach to easily assess results, and integrate the database aforementioned, as well as characterization factors discussed before.

89 Conclusions

Human activities have been causing socio-economic pressures and threatening biodiversity for years. At present, 90 % of goods are transported by ships around the world. To tackle environmental problems, LCAs have been performed in the maritime industry, but studies have mainly focused on specific lifecycle phases.

At present, several LCA methodological approaches are set in maritime industry, this being a problem regarding result's reliability. Hence it would be interesting to create a LCA standard, but prior this work, an analysis of LCA's methodological trends in maritime industry is necessary. This work has not been done for the moment and reflects the scientific contribution of the article.

Hence, the present review was intended to serve as a basis to a future LCA standard and to answer the following research question: How have holistic LCA studies been conducted up to now and to what extent do the methodological tendencies meet recommendations contained in European standards? As LCA results greatly rely on methodological choices, we chose to focus our analysis on this aspect whether assessing LCIA values.

Starting from a sample of 32 articles, we identified current main trends concerning key LCA aspects, and set out guidelines regarding methodological lacunae.

It is important to highlight the diversity of materials and functions served by different types of vessels, but the scientific literature mainly focuses on steel ships built for transport, doubtless because regulations mainly concern this type of vessel. Studies have mostly been conducted in Europe and Asia, countries where the world's largest shipbuilders and shipping companies are based.

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10 Also, a-growing number of LCA initiatives have been launched,
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12 and more and more data have become available, especially since 2014.
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17 Methodological trends regarding each key LCA topics were discussed. For the moment, two
18 methodological trends meet European guidelines: normalization and weighting. For others, avenues
19 of research were presented in order to meet European requirements and discuss a LCA standard. This
20 standard should be accompanied with the creation of public, transparent, and
21 reliable LCA software and database in order to help disseminate it in the maritime companies.
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36 10 Compliance with ethical standards

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42 The authors have no competing interests to declare that are relevant to the content of this article.
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