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Life cycle model and metrics in shipbuilding: how to use them in the preliminary design phases

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Abstract

Maritime vessels are complex products with long service life and great costs of building, manning, operating, maintaining and repairing. The paper aims to introduce a specific life cycle model and related metrics in shipbuilding design, supporting decision-making processes of material selection, manufacturing/assembly practices, maintenance, use, etc. The model provides a common structure for life cycle assessment (LCA) and life cycle cost analysis (LCCA) including the way to retrieve and to collect necessary data for the analysis starting from the available project documentation and design models. Different design configurations (materials, welding methods, etc.) for hull and hatches of a luxury yacht have been analysed using the proposed model.

Keywords: LCCA; LCA; shipbuilding; design; maritime vessels.

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1. Introduction

The project of large and complex products like ships, ferries and offshore vessels is a long process which includes all the activities until the product delivery (design phase, construction phase, etc.). It is widely known that decisions made during the early design phases have a great impact on the overall life cycle (e.g. costs, performances, etc.). Life cycle management is a challenging task for maritime transportation means, which have long lifespans (more than 15-20 years) and different operative scenarios. In addition, new environmental regulations and market requirements in this field require to consider life cycle aspects during the design phase [1].

Starting from the last decade, life cycle approaches have been applied in shipbuilding. Life cycle assessment (LCA) allows to calculate products/services environmental load [2]. Life cycle costing analysis (LCCA) allows the assessment of acquisition, running (e.g. fuel consumptions, operations, service, etc.) and disposing costs [3].

This paper aims to define a suitable life cycle model and metrics for environmental and cost analyses in shipbuilding. In particular, research objectives are: (i) to develop a consistent and robust methodology for life cycle evaluation, (ii) to establish a framework for life cycle inventory starting from available project documentation and, (iii) to provide life cycle indicators (both economic and environmental) as design metric for long-term decision making strategies. The novelty of the paper is the integration of ad-hoc and fragmented methods into a common standard for life cycle analysis in shipbuilding and ship design. The paper is structured as follow: after literature analysis in this field (§2), the proposed framework is described (§3). Different configurations of materials and manufacturing processes used to develop hull

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and hatches of a luxury yacht are analyzed (§4) and obtained results are reported (§5). Lastly, conclusions and future work are proposed (§6).

2. State of the art about life cycle in ship design

Maritime vessels are complex products that follow, as standard practice, the traditional flow of product design [4]. Traditional design workflow encompass requires elicitation, conceptual design, embodiment design and detail design [5]. It is well known, however, that this niche market requires specific paradigms that need to be developed properly to take into account specific design constrains and requirements [6]. In particular, requirements are resulting from the purpose of the vessel and the operative use scenario. An overview of vessel typologies is presented in Fig. 1.

Yachts (sail and motor yachts) Passenger ferries (Ro-Pax, etc.)

Cruise ships Merchant ships (cargo, tanker, etc.)

Fishing vessels Others (pipe laying vessels, etc.)

Fig. 1. Main vessel typologies.

Although vessels are different in size and typologies, common functional groups can be identified: (i) *Hull and superstructure*, (ii) *Outfitting*, (iii) *Machinery and propulsion*, (iv) *Electrical navigation and communication*, (v) *Piping system*, (vi) *HVAC*, (vii) *Accommodation*, (viii) *Painting and insulation* [7,8,9]. Each group (building module) can be further divided into other subgroups.

Due to product complexity, ship design and shipbuilding are becoming integrated activities and players involved in these processes are large in number. In this context, information and data sharing needs to be managed in an efficient way. Different design suites for project life cycle management have been developed in recent years to cope this problem [10,11]. Product lifecycle management (PLM) and product data management (PDM) are increasingly deployed in the maritime vessel design and construction phases with the aim to manage large amounts of data [12]. However, these systems are not decision-making tools able to decrease product costs and environmental loads throughout the entire lifetime [13]. The use of those design suites is limited until the vessel delivery without any extension to the service life. An extension of this boundary can be done for supporting the handover process from the shipyard to the vessel owner. Indeed, most of the information required for the correct management of the vessel are part of the project documentation stored in those repositories [14]. A life cycle analysis implies an holistic life cycle approach which goes further than cost and environmental assessment until vessel delivery. LCA is a standardized approach for environmental assessments of products and services, addressing their potential impacts with a cradle-to-grave perspective. LCA allows to establish environmental oriented guidelines and it can be applied in different fields and human activities [2]. LCCA is a well-known method in this field for the analysis of product/service life cycle costs, including running costs (e.g. fuel consumptions, service/maintenance, etc.). LCCA approach is used by designers/engineers in the project cost management as well as by potential buyer in the purchasing decision process [3]. LCA and LCCA methods have been developed for different purpose and, in most of the cases, they use different models, boundary conditions and data inputs. Literature highlights few case studies on LCA [15,16,17] and LCCA [18,19] of maritime vessels. Several issues have been identified concerning the use of LCA/LCCA in shipbuilding such as: (i) fragmented tools [20], (ii) data sharing among design departments [21], (iii) time-consuming data collection (inventory) [22] and, (iv) how to use the assessment results [23].

3. Method and metrics

This section describes, firstly, how life cycle model has been defined considering the peculiarities of shipbuilding context and, secondly, how the environmental metrics have been characterized

3.1. Proposed lifecycle model

The proposed model starts with the analysis of existing frameworks and standards in other context. For example, ISO-15686 standard (Buildings and constructed assets - Service-life planning) has been used as bases to perform lifecycle cost analysis. Likewise, ISO-14040 standard (Environmental management - Life cycle assessment) has been used for the environmental assessments. The two standards have not been developed for the life cycle analysis in shipbuilding context but they can be adjusted based on the specific needs of this field. In both cases, it is necessary to introduce the concept of *"functional unit"* [2]. The definition of the functional unit is a key aspect: it allows to make a comparison among different vessel typologies as well as to create a correct inventory model in which inputs and outputs are attributed to the reference flow (product system). Functional unit has been defined as "*the construction and the disposal of vessel modules for the transportation of persons, goods and/or operational activities by sea for a period of 20 years*". It is worth to notice that functional unit allows to consider the construction and the disposal of the overall vessel or part of it (modules). So doing, module alternatives can be analyzed including the impact in the overall system and across the vessel lifespan. A lifespan of 20 years has been chosen considering the average life of vessel typologies [24]. Based on the functional unit, the system boundaries have been defined and they include: (i) materials and manufacturing, (ii) use phase and, (iii) end-of-life). The model system boundary is shown in Fig. 2. It is worth to notice that only energy-intensive manufacturing processes (e.g. welding, cutting, moulding, etc.) have been included in the model due to the fact that the inventory for these processes can be performed in a robust way by using design documentation (CAD, excel files, etc.).

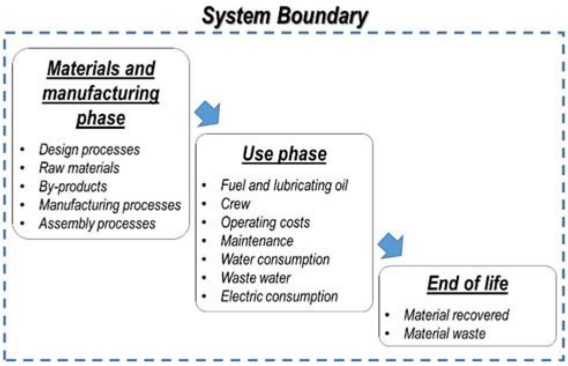

Fig. 2. Model system boundary.

Although considered standards provide criteria to include transportation of raw materials and by-products, this phase is not considered in the model due to negligible contribution on the overall impacts (both environmental and economic) [24].

Regarding LCA, total environmental impact (EI_{tot}) is calculating considering the contribution of each life cycle phase included in the system boundary. For the materials and manufacturing phase, raw materials extraction (EI_{rm}), production of by-products (EI_{bp}) and the assembly operations (EI_{as}) have been included in the model. For the use phase, the impacts deriving from fuel/oil consumption (EI_{fu}), water (EI_{wa}) and electricity consumption (EI_{el}), maintenance/service (EI_{ma}) and wastewater production (EI_{ww}) have been included in the model. For the end-of-life phase, the environmental benefits of materials recovery (Eb_{mr}) or the impacts related to the material waste (EI_{mw}) have been included. Equation (1) summarized environmental items included in the LCA model.

$$\begin{aligned} EI_{tot} &= \left(EI_{rm} + EI_{bp} + EI_{as}\right) + \\ &\left(EI_{fu} + EI_{wa} + EI_{el} + EI_{ma} + EI_{ww}\right) + \\ &\left(Eb_{mr} + EI_{mw}\right) \end{aligned} \tag{1}$$

Regarding LCCA, total life cycle cost (C_{tot}) is calculated considering the same functional unit and system boundary of the proposed model. For the materials and manufacturing phase, design costs (C_{de}), raw materials costs (C_{rm}), manufacturing activities costs (C_{ma}) and assembly costs (C_{as}) have been included in the model. Use phase cost (C_{use}) and end-of-life phase cost (C_{eol}) have been included in the model as well. For those two cost items, cost actualization is mandatory due to the long lifetime of this kind of means. Equation (2) summarized costs items included in the LCCA model.

$$C_{tot} = C_{de} + C_{rm} + C_{ma} + C_{as} + \sum_{t=0}^{T} \frac{C_{use}}{(1+i)^t} + \frac{C_{eol}}{(1+i)^T} \tag{2}$$

In the Equation (2), C_{use} and C_{eol} represent respectively the total discounted costs of use phase and end-of-life phase, where “i” is the discount rate and “t” the reference period. The subscript “t” used for C_{use} item means that values are referred to the t-th year. For C_{eol} item the actualization is performed at the T-th year which is the disposal year of the vessel (T=20 years as per functional unit definition).

3.2. Lifecycle metrics

ReCiPe mid-point has been chosen as life cycle impact assessment (LCIA) method to characterize life cycle impacts [25]. Since this study is oriented to the shipbuilding, energy, pollution and natural resources are of primary importance. To address this perspective, Human Health (HH) and Resources (RA) mid-point impact categories have been used. The default ReCiPe mid-point method perspective used is the Hierarchist (H) version has referred to the normalisation values of Europe. Perspective H is based on the most common policy principles with regards to 100 [year] timeframe (as referenced in the ISO 14044:2006 standards on LCA).

Only a single indicator has been used for LCCA and it represent the overall life cycle cost (C_{tot}) [€] of the vessel.

4. General framework for life cycle data collection

The proposed lifecycle model has been developed to be used in preliminary design phases (late conceptual design phase or embodiment design phase). Both LCA and LCCA use the same model with different metrics for the assessment of environmental and cost performances. A framework for the data collection and analysis is presented in Fig. 3.

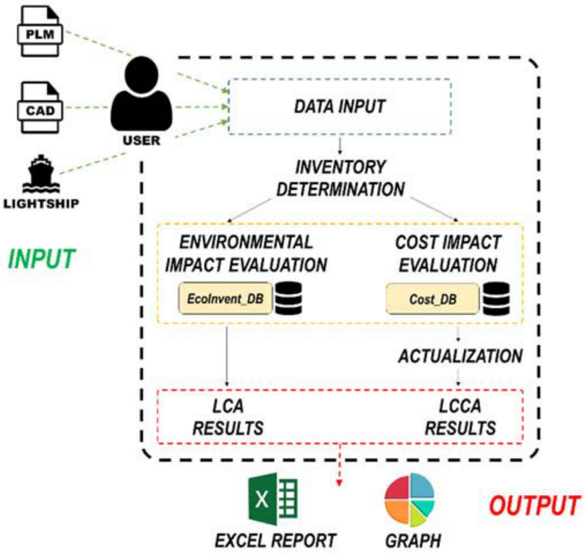

Fig. 3. Framework for life cycle data collection.

The master document for the data collection is the lightship-weight project document. The lightship-weight is an excel file, defined by the shipbuilders during the design phase, which contains a detailed list of components with relevant weight and materials starting from the MTO. In this list the deadweight like fuel, cargo, water, passengers, etc. are not considered. The lightship-weight document is composed by thousands of items which are organized following the modules (functional groups) classification previously defined. As example, an extract of the *Hull and superstructure* module is reported (Fig. 4).

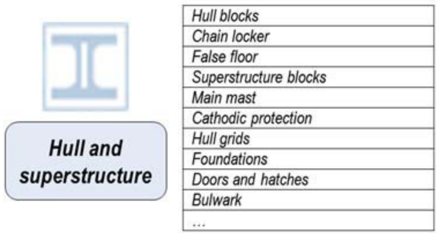

Fig. 4. Extract of lightship-weight document for *Hull and superstructure*.

In order to get all the necessary information for the lifecycle analysis, the lightship-weight file needs to be coupled with other project documents. In particular, further useful lifecycle data can be retrieved from the documents stored in the PLM tool, especially for commercial and standard products (e.g. engines, generators, etc.), as well as from the CAD system (dimensions, welding length, etc.). All the mentioned documents feed the lifecycle model with input data necessary to perform the subsequent analysis.

For LCCA inventory, foreground data are collected from lightship-weight project document and they are used to estimate raw materials costs, manufacturing costs and assembly costs using in-house Cost_DB. Cost_DB stores unitary cost (background data) of materials and labor and it is regularly updated. Costs of standard and commercial parts purchased from suppliers are acquired directly from the PLM. Running costs of the use phase are estimated using shipyards' knowledge (e.g. operating costs, maintenance costs, etc.) and characterizing specific use scenarios on the basis of the expected vessel utilization (travelled hours, speeds, etc.). Disposal costs and revenues are preliminary addressed within the Cost_DB, even they are suffering from a large uncertainty.

For LCA inventory, the same foreground data of LCCA coming from project documentation are used (materials, parts' weight, etc.). In this case, the assessment of the environmental impacts is performed using background data coming from EcoInvent_DB. LCA results are calculated using dedicated LCA tool (e.g. SimaPro).

5. Case study: a luxury motor-yacht

The described approach has been used to perform the LCA and LCCA analysis of a 50 [m] yacht designed by an Italian shipyard. General drawing and technical specifications of the yacht are reported in Fig. 5.

Functional unit has been defined in accordance with proposed model: "*the construction and the disposal of a vessel for the transportation of persons, goods and/or operational activities by sea for a period of 20 years*.

Length overall	49.8 [m]
Number of decks	3
Gross tonnage	Less than 500 [GT]

Fig. 5. Drawing and technical specification of mono hull motor-yacht.

Life cycle inventory has been carried out based on the proposed framework and the original product configuration defined by the shipyard (all structural parts made in carbon steel). A typical scenario of 500 [hrs/year] travelling hours per year has been modeled for the use phase. This scenario can be considered the most common one for this kind of vessel, which is usually used during the summer period in the Mediterranean Sea. For the water consumption of cleaning/washing operations, surface dimensions of the hull and superstructure have been considered. Crews and personnel have been estimated based on the overall yacht length. The considered items are reported in Table 1.

Table 1. Items considered for the use phase modelling of the first solution.

Use item	Value
Fuel (MDO) (generators)	216000 [l/year]
Fuel (MDO) (engines)	180250 [l/year]
Maintenance	Antifouling treatment (1 year)
	Safety and fire system surveys (1 year)
	Anodes inspection and replacement (2 years)
	Batteries and accumulator replacement (7 years)
	Painting (5 years)
	Special surveys I (5 years)
	Special surveys II (10 years)
	Special surveys III (15 years)
Water	Approx 1000000 [l/year]
Waste water	Approx. 25000 [l/year]
Personnel	9 people: 1 captain, 1 chief officer, 1 chief engineer, 1 deckhands, 3 stewards, 1 cook and 1 chef
Electricity	216000 [kWh/year] electric energy consumption @ pier
Operating costs	Berthing and Insurance

As reported above, the first solution investigated by the shipyard is to build all structural parts of the motor-yacht using carbon steel material and shielded metal arc welding (SMAW) technology. Structural parts mainly involve items classified in the *Hull and superstructure* module such as (i) hull blocks, (ii) hull grids, (iii) foundations and, (iv) hatches. Those items are critical in terms of environmental impacts as identified in a previous work and they count more than 40%

in relation to total environmental impacts of the materials and manufacturing phase [7]. They are also relevant in terms of life cycle cost but with lower importance (approx. 25%) due to the specificity of this kind of vessel. Indeed, luxury items are present in the accommodation and outfitting modules changing the share of manufacturing costs.

Starting from this initial configuration, a set of alternatives have been evaluated considering technical feasibility in terms of design constraints, manufacturability, compliance with standards (IMO and/or Lloyd's Register), etc. Table 2 reports the four analysed design configurations considering the mentioned items in terms of material and main manufacturing processes. Design alternatives (plates configuration and arrangement, plates thicknesses, technical drawing, etc.) have been developed by the engineering team of the shipyard.

Table 2. Possible design configurations for hull and hatches.

N. #	Hull blocks, Hull grids and Foundations		Hatches	
	Material	Manufacturing	Material	Manufacturing
01	Carbon steel	Laser cutting, SMAW	Carbon steel	Laser cutting, SMAW
02	Carbon steel	Laser cutting, SMAW	Carbon fibre composite	Resin infusion
03	Aluminium	Laser cutting, GTAW	Aluminium	Laser cutting, GTAW
04	Aluminium	Laser cutting, GTAW	Carbon fibre composite	Resin infusion moulding

Comparison of design alternatives has been performed analysing only those items that differ among the four configurations. For materials and manufacturing phase, items involved in the analysis are reported in Table 2. All the other modules and items have been kept unchanged (including *machinery and propulsion* module). For use phase, fuel consumption (engines) and maintenance items are the only ones that show a difference in the considered configurations. Maintenance has an impact in those configurations with carbon fibre composite materials (#02 and #04), even if its contribution can be considered negligible. Fuel consumption (engines) is related to the yachts' weight reduction as reported in Table 3. In particular, cruising fuel consumption has been estimated considering engine performances (Caterpillar C32 tier II EPA engines) provided by the engine manufacturer (Caterpillar). Engine performance tables correlate the cruising speed with engines speed and their specific consumption based on the overall weight of the considered configurations. Table 3 provides an overview of marine diesel oil (MDO) consumption for the design configurations.

Table 3. Fuel consumptions of the four hull/hatches configurations.

N.	Hull blocks, Hull grids and foundations weight	Hatches weight	Fuel (MDO) consumption for 500 [hrs/year]
01	126 [ton]	3 [ton]	180250 [l/year]
02	126 [ton]	1,5 [ton]	179395 [l/year]
03	68 [ton]	2 [ton]	152691 [l/year]
04	68 [ton]	1,5 [ton]	152249 [l/year]

For EoL phase, the following scenarios reported in Table 4 have been considered for the analyzed materials. The proposed scenarios have been defined based on the current available technologies in this sector.

Table 4. EoL scenarios for the considered materials.

Material	EoL scenario
Carbon steel	Recycling 95%, Landfilling 5% [27]
Aluminium	Recycling 95%, Landfilling 5% [26]
Carbon fibre composite	Recycling 10%, Landfilling 90% [16]

6. Results discussion

In this section, results of environmental and economic impacts are summarized. For LCA analysis, SimaPro 8.1 (with Ecoinvent 3.1 database for background data) has been used. Fig. 6 shows the environmental impacts of the design alternatives (ReCiPe mid-point impact assessment method). From the assessment emerges that the two aluminum hull configurations (#03 and #04) present a lower impact for each indicator, especially for Ecotoxicity and Metal Depletion. Moreover, it can be noticed that the use of carbon fibre hatches does not bring significant improvements. Fig. 7 shows the impacts breakdown in different life cycle phases for the design configuration #04 which is the most promising from the environmental point of view. This graph highlights relevant impacts related to the use phase in particular for ozone and fossil fuel depletion indicators. The same behavior can be noticed for the other three configurations.

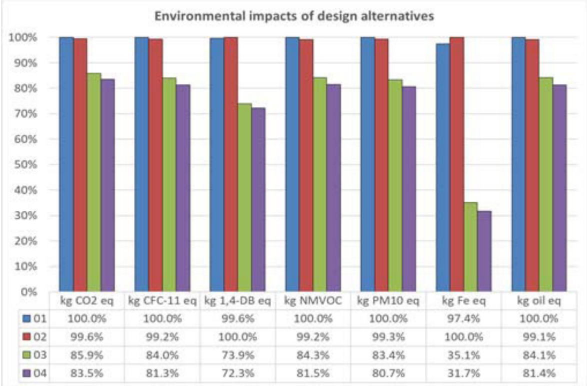

Fig. 6. LCA assessment of the four design configurations

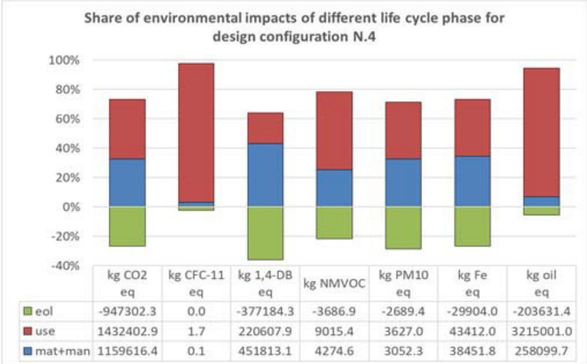

Fig. 7. Manufacturing, use and EoL phases' assessment of configuration #04

LCCA results are reported in Fig. 8. Here, the discounted life cycle cost (considering manufacturing, use and disposal phases) for each design configurations are represented. Even if the manufacturing cost of the aluminium hull is higher than the steel one (+20%), the life cycle cost is lower due to the reduction of fuel consumption during the use phase. Again, as for the LCA, the use of carbon fibre hatches does not play a significant role in reducing economic footprint.

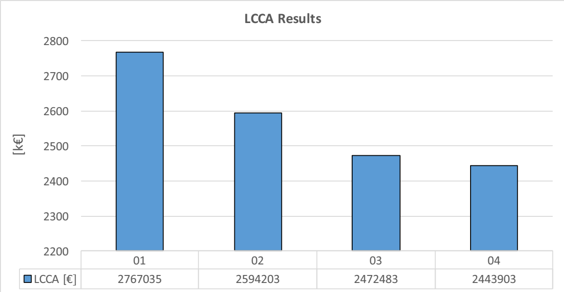

Fig. 8. Total life cycle cost of the four design configurations

Although many researchers have analyzed the LCA/LCCA of marine transportation means, more work is needed to establish a practical and standardized approach for the assessment of this kind of products. In this context, the case study demonstrates how this method can be used to compare design alternatives during the early design phase from a life cycle perspective, using dedicated metrics.

7. Conclusions and future work

In this work, a complete model with dedicated metrics for the analysis of lifecycle performances in shipbuilding have been presented. It combines state-of-art concepts and best practice in this sector, creating a novel framework for a standardized design approach. Thanks to this model, different product alternatives can be evaluated in the preliminary design phases increasing engineers' awareness about environmental and economic impacts with a life cycle perspective. Reported case study highlights the effectiveness of this method, showing a comparison between four different design configurations of a luxury yacht and indicating the most sustainable one. For these reasons, this model can be considered an efficient and effective tool for decision-making strategies and for supporting designers in reducing lifecycle environmental and costs impacts. Moreover, this model is beneficial for ship owner which can know, in advance, impacts of design choices in different operative scenarios. Future work will be focused on the estimation of data inputs uncertainty due to the long life span of this kind of products. Indeed, in order to have better future projections, parametric inputs with statistic distributions are recommended instead of deterministic inputs that do not be varied along the vessels life cycle.

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