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Life Cycle Sustainability Assessment of ENDURUNS Project: Autonomous Marine Vehicles

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Abstract. The autonomous marine vehicles development has a grow demand by offshore industries. The multiple facilities implemented in this environment requires the evolution of this devices for several task as survey, maintenance or monitorization. The technology complexity of this devices requires great efforts in economics and resources to innovate. In this line, the ENDURUNS project purposes to design an autonomous marine system capable to performance a long endurance during the missions due to the employment of renewable energies for its vehicles. The evaluation of the project life cycle represents an important task for the project management. In this article, it is exposed the three different project life cycle aspects. The aspect analyzed are the social life cycle assessment, the life cycle cost and the life cycle assessment. It has been applied the corresponding standards in the European context to develop each methodology and to obtain the results. Thus, this work brings an approach about the environment, economic and social impact of this project. The results presented from this study can be considered for practitioners for future research in marine mobility field, due to the sustainability characteristics of the project analyzed. **Keywords:** Sustainability, Life cycle, Marine vehicles, Renewable energy sources, Project management.

1 Introduction

In the last years, the marine industry has been suffered a great evolution. Different sectors have implemented systems and services in this environment, e.g., novelous oil, gas or renewable energies installations. These activities requires the employment of complex vehicles and tools to monitor or operate their facilities [1]. In this context grows the autonomous marine vehicles technologies and advancements, since up to now they were only focused on military, research or entertainment labors. Currently, these devices are essential in different applications as maintenance or building in offshore industries [2].

The autonomous marine vehicle systems, like any other product or service, requires complying with the current environmental or standardized policies in this field. The manufacturing of these devices generates wastes and emissions that must be counted and managed [3]. There are various organizations and institutions committed in this role. Since 2011,

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the United Nations Climate Change Convention (UNFCCC) has been working in the environment protection , during this event was concluded that the main contribution for global warming is the Green House Gas Emissions (GHG) and must be limited by the governments and companies [4]. The successive Climate Conferences of Parties (COPs) have been substantiated the restrictions and measures to reduce the GHG in different areas and industries around the world [5]. In marine issues, the main organism in charge is the International Maritime Organism (IMO) committed to drive the policies in offshore activities [6].

This kind of devices is a small portion of the total of marine vehicles. Nevertheless, the manufacturing of a project requires to study the consequences in terms of environment impact to consider it sustainability and footprint, but also in other linked aspects as economic or social [7, 8]. Following the guidelines and standards of each aspect, this article tries to verify the premise of the project in sustainability terms [9]. The scope of the study can be considered as preliminary results due to the project is ongoing a could suffer some minor changes relative to materials or measurements. The article is structured as follow:

- The case of study is presented in the section 2. In this point it is possible to learn with details about ENDURUNS project and its motivations. Also, it is described the LC fundaments and principles.
- The section 3 details the LCA of the project. It has been presented the results obtained with graphical and numerical representation.
- The LCC study has been exposed in the section 4 with a wide economical project analysis with different investment scenarios.
- In section 4, it is presented an approach about the SLCA implications of the project.
- Finally, the section 5 summarizes the main conclusions and results extracted from the different previous sections.

2 Case of Study

The ENDURUNS project born in this context with the challenge to develop low environment impact during its performance. This purpose is in the framework of European Comission "Horizon 2020" guidelines. This project attempt to design a long endurance system to map and survey the seabed using renewable energies (hydrogen fuel cell and photovoltaic cells) in the autonomous marine vehicles developed [10]. The ENDURUNS project, aims to bring a change in the field of offshore research activities, prioritising the automation and energy optimization during the inspection of large areas of the seabed and other activities (surveillance, research, maintenance, etc.) [11]. The system is constituted by the devices or vehicles deployed at sea and from a remote-control centre onshore that will be in charge of monitoring. All of this will be managed by a communications and IT infrastructure system [12], this last items has been apportioned in the vehicles model estimations for this study [10].

The AUV designed is equipped with a fuel cell system using hydrogen as an energy source. Hydrogen and fuel cells have higher specific energies than conventional batteries, which in turn translates into higher amounts of power for the AUV [13]. Another added advantage of hydrogen technology concerns with the storage technology and in consequence with the availability of the vehicle without surface wire-based link [14].

The other vehicle of the project, called as USV, has been designed to act as a mothership for the AUV, but also to facilitate communication between the ENDURUNS remote control centre and the AUV when it is operating at depth [15]. The USV also transmits information to the AUV to confirm its exact position in the mission territory, with the objective of providing high quality geo-referencing data. The USV has been designed to be compact and

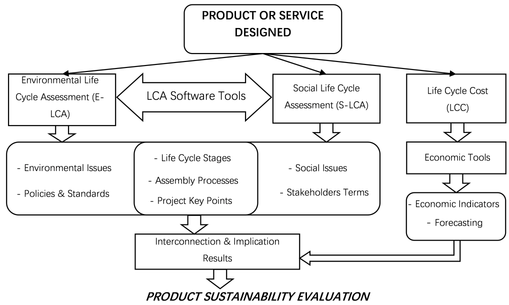

Figure 1. LCSA Block Diagram for the project evaluation

lightweight, at 7 meters long and 2 meters wide, made of glass fibre reinforced composite with resin infusion moulding [16]. It is a 100% electric vehicle, with a power unit consisting of a rechargeable lithium-ion (Li-ion) battery, powered by flexible photovoltaic panels made of monocrystalline silicon [17].

The Life Cycle Sustainability Assessment (LCSA) do not comprehend only the environmental fact as conclude Purvis et al. in 2019 [18].Previously, the United Nations inside agenda 21 program made a first warmed to link the social and economic dimension with the environmental aspect to achieve a sustainable development [19]. Thus, it is possible to define the study of the LC pillar in three different points, assuming different grades of maturity and data availability due the literature apparition and evolution [20].

- The environmental footprint of a product or service during their LC represent the most relevant point to determinate its sustainability. Since the GHG and wastes generated during the successive LC phases affect directly to the environment. To analyze the relation between inputs and outputs of a product LC and its environmental consequences is stablished the LCA standards, International Standard Organization (ISO) 14000 series [21].
- The economic evaluation requires the application of mathematical tools to determinate the costs and investments of a product or service during its LC. Due to the market nature, this matter can be inaccurate, however it is possible to obtain a good approach following the guidelines and methods marked by SETAC in 2011 [22] and refined in the last years with the EN/IEC 60300-3-3 for LCC measurements [23].
- The social dimension is the most immature matter added to the products and services LC impacts. The human engagements during the different phases of a product LC generates positives or negatives social impacts in a determinate community among stakeholders, customers, and producers. The methodology framework is guided by UNEP/SETAC in 2009 and it is still in development with the last upgrade in 2020 [24].

Therefore, there is important to analyze each dimension of this project to affirm that achieves the goals of sustainability being the LCSA=LCA+LCC+SLCA as conceptual equation representation. This documentation supposes an added value for the project and it enables to lead a determinate market segment [25]. Thus, the connection of the three aspects can be defined by the following figure 1 diagram, based on a recent work [26]:

2.1 Life Cycle Assessment

The standard guidelines to evaluate the environmental impacts were founded in Paris by the SETAC code of practice in 1993. The technical committee published the ISO 14000 series

Table 1. ENDURUNS project LCA Inventory

		INPUTS					OUTPUTS		
PROCESSES	SUB-PROCESSES (AUV & USV)	RAW MATERIALS	ENERGY	WATER	AIR	TRANSPORTATION	AIRBORNE	SOLID	WATERBORNE
Manufacturing	Components	X	X	X	X	X	X	X	X
Vehicle Assembly	Assembly	X	X	X	X			X	X
Set Up	Suppliers Shipping					X	X		
	Pre-Launch Test		X	X	X			X	X
	Post-Launch Test		X					X	X
Launch	Displacement		X			X	X	X	
	Raising Operations		X				X	X	
Use	Fuel Consumption	X							X
	Recharge Operations		X			X			
Maintenance	Displacement					X	X		
	Maintenance Operations	X	X					X	
Dismantling	Displacement		X			X	X	X	
	Raising Operations		X				X	X	
	Dismantling Operations		X		X		X	X	X
Recycling	Recycling Operations		X	X	X	X	X	X	X

with the aim of environmental management [27]. The ISO 14040 standard describes with detail the methodology to elaborate the study in terms of environmental impacts of a product or service LC. In this work, it has been followed this guideline to obtain the ENDURUNS project results. In the following points, it is drafted the methodology phases and its relationship in the analysis reviewed by several authors as J. Pryshlakivsky and C. Searcy in [28].

The methodology has been executed with the specialized software SimaPro. This support is necessary due to the great volume of information that comprises a product LC. The data base employed by this tool is the Ecoinvent, one of the most comprehensive and used of the market as proves Z. Barahmand and M.S. Eikeland in [29]. The methodology phases have been detailed in the following points.

(1) Goal and scope

This phase makes an overall description of the system, product or service analysed. In this part is defined the system boundaries and the correspond functional unit [30]. The ENDURUNS project develops a semiautonomous survey system composed by two vehicles and a control centre as physical equipments, but also different softwares and IT tools, resulting each of one as functional unit in this study [31].

(2) Inventory

In this phase it is resumed the relation of inputs and outputs of the different project stages. The inputs are defined by the raw materials, energy, water, air or transportations employed during the LC. The outputs are identified by the airborne emissions, solid waste and waterborne [32]. The stages of the project LC have been structured as follows: Manufacturing, Vehicle Assembly, Set-Up, Launch, Use & Maintenance, Dismantling and Recycling. Thus, the study obtains high level of detail which it is called as "cradle to grave" LC [33]. The substances involved along the stages of the project LC have been computed in the software to define the inputs-outputs flows. The following table 1 summarizes the LC stages and the processes employed for the study.

(3) Impact assessment

Based in the previous point, this phase evaluates throughout a determinate methodology with the reference of the International Life Cycle Data system (ILCD) recommendations

Table 2. LCA results

Damage Category	Unidad	Total	AUV	USV
Human Health (Carcinogens, Resp. Organics, Resp. Inorganics, Climate Change, Radiation, Ozone Layer)	DALY	0.036	0.014	0.022
Ecosystem Quality (Ecotoxicity, Acidification, Land Use)	PDF*m2yr	9107.24	3439.71	5667.53
Resources (Minerals, Fossil Fuels)	MJ surplus	44556.79	34214.79	10341.99

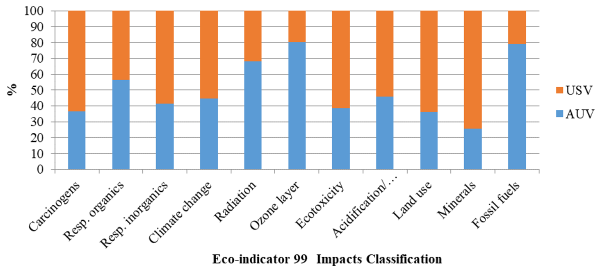

Figure 2. ENDURUNS vehicles damage impact categories percentage contribution

the environmental impact that the processes analysed generates [34]. In this case, it has been implemented the Eco Indicator 99 commonly used in European context LCAs studies [35]. This methodology divides the environmental impact into three different categories, detailing the total results in table 2, together with the ENDURUNS vehicles comparison of each damage categories impact in percentage terms showed in figure 2, higher for USV in Human Health and Ecosystem Quality categories.

(4) Interpretation

This phase develops an evaluation in relation to the results obtained in the previous phase. It is possible to identify the hotspots in terms of environment impact along the project LC. This phase allows to make decision making management to optimize a project in terms of sustainability. Also, this point serves as auditory with the committed authorities with the corresponding documentation and certifications [36].

In figure 2, it is possible to observe each vehicle contribution for the different impact categories, highlighting the AUV values in ozone layer and fossil fuel, in relation with the use (fuel consumption) and manufacturing (components) stages. Thus, it can be purposed the use of more sustainable components and to optimize the AUV.

2.2 Life Cycle Cost

The first studies about cost identification inside the product processes were published during 90's decade and one of the most relevant was developed by Blanchard and Fabricky in [37]. In these days, the LCC studies goes in the line of research with artificial intelligence or machine learning techniques as X. Gao and P. Pishdad-Bozorgo analyses in [38], to optimize the companies and organizations manufacturing processes in early stages. In marine industry field exist different works in LCC matter as the published by S. Wolff et al. in [39], discussing the renewable energies LCC in heavy-duty vehicles and most recently in 2022 the LCC research in dual fuel marine engine for ships versus conventional developed by K.Q. Bui et al. in [40].

The methodology used was established by the European normative UNE-EN-60300-3-3 in 2004. To carry out the LCC model, a series of distinct stages will be followed. According

Table 3. ENDURUNS project incomes scenarios

INCOMES	SCENARIOS					
	Pessimistic €/year	Total €	Average €/year	Total €	Optimistic €/year	Total €
Fundings	150.000	1500.000	300.000	3000.000	450.000	4500.000
Mission Receipt	40.000	400.000	100.000	1000.000	160.000	1600.000

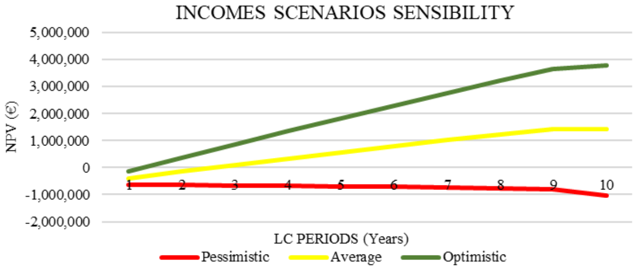

Figure 3. ENDURUNS project NPV scenarios

to the UNE standard, the stages that make up the model are ten. Although the standard distinguishes between these ten stages, each model has its own flexibility and application, so before selecting a model, it is necessary to identify what information is available and what results are expected [41]. As it is a long-term study, many of these data are not available at the time of the study, so these data must be estimated. Like any model, a LCC model is a simplified representation of reality. Costs will be estimated by relating them to the most salient features and aspects extracted from the product.

The first step to develop the LCC study is the configuration of a Cost Breakdown Structure (CBS) defined by Acquisition, Ownership and Disposal costs in this case. These three contributions are partitioned in different elemental cost as Capital, Installation, Operation, Maintenance, Transport, and other cost. With this information, it is possible to define the corresponding cost and fee matrices with a determinate amortization method and remaining value [42]. Then, for this study model it is supposed different incomes scenarios (fundings and mission receipts), displayed in table 3 with a remaining value at the end life of 10 %.

To obtain the results, it has been used the net present value (NPV), defined in Eq. (1) with 1% discount rate k to evaluate the profitability of the project, with an annual amortization with own founds (no bank loan) strategy based on [43]. The cash flows are represented by CF, the initial investment I_0 (acquisition cost in this case), the life cycle periods t and the end-of-life period T.

$$NPV = -I_o + \sum_{t=1}^{T} \frac{CF_t}{(1+k)^t}. \tag{1}$$

In figure 3, it is showed the NPV sensibility model taking in account the incomes assumptions. It is observed that only the optimistic and average scenario achieves positive values at the ENDURUNS project end of life. Also, it is possible to observe the influence of the disposal cost occurred in the last period.

Table 4. ENDURUNS project SLCA model goal & scope

<table>
<tr><td>PARTNERS</td><td>HAN</td><td>ALT</td><td>GRA</td><td>COM</td><td>ENG</td><td>SPA</td><td>ONA</td><td>MET</td><td>KLA</td><td>HYS</td><td>ZGR</td><td>SWI</td><td>UNI</td><td>UCL</td><td>NAT</td><td>CON</td><td>TUC</td></tr>
<tr><td>ORIGIN</td><td>Korea</td><td>Greece</td><td>Italy</td><td>France</td><td>Cyprus</td><td>Belgium</td><td>Italy</td><td>Lithuania</td><td>Lithuania</td><td>Italy</td><td>Greece</td><td>Cyprus</td><td>United Kingdom</td><td>Spain</td><td>Greece</td><td>Italy</td><td>Denmark</td></tr>
<tr><td>WORKING HOURS (workers/month)</td><td>44</td><td>99</td><td>83</td><td>62</td><td>38</td><td>44</td><td>48</td><td>48</td><td>48</td><td>81</td><td>40</td><td>37</td><td>64</td><td>55</td><td>70</td><td>74</td><td>43</td></tr>
<tr><td>FUNTIONAL UNIT</td><td colspan="17">ENDURUNS AUV & USV</td></tr>
<tr><td>INDICATORS</td><td colspan="17">Freedom of Associations & Unions - Fair Salary - Child Labor - Discrimination/Equality - Health& Safety - Local Employment - Access to Resources - Living Conditions - Product Utility - Public Commitments - Corruption - Fair Competition - Intellectual Property Rights - Supplier Issues - Consumers Issues</td></tr>
</table>

2.3 Social Life Cycle Assessment

As mentioned in the introduction point, the SLCA of a product or service LC is the last reviewed aspect around the sustainability concept [44]. The SLCA evaluates the socioeconomic implications and consequences of a product or service existence. Thus, it is necessary to declare and asses positive and negative impacts during the LC stages [45]. However, it is quite tedious to quantify and determine this point due to the product or service dimensions. There are several parts involved, workers, factories, society, culture, or governments in a SLCA. In this study, for instance, there are numerous partners and suppliers to configurate the ENDURUNS systems. For these reasons, it has been taken different assumptions to fill the missing data with external bibliography or databases. It is possible to divide this analysis in two well defined phases that it has been described in the following points [46].

(1) Goal and scope

In this phase is defined the system boundaries, stakeholders and the social categories that will be analysed in the study. This is a key part of the methodology and mark the pathway criteria as the functional unit, cut off or impact assessment method [47]. In table 4, it is defined this information.

(2) Social life cycle inventory (S-LCI)

This phase defines the inputs and output flows in the social impact's indicators identified. The ENDURUNS product and systems LC data has been quantify and computed in different categories and subcategories following the standard. These flows can be normalized as an activity variable, by G.A. Norris in 2006 [48] and the rest until now are defined the working hours as data reference to produce a functional unit [49].

In the following table 5 is exposed the model approach for the ENDURUNS project SLCA. The results have been averaged among the different partners data and some data base as International Labour Organization ILOSTAT [50]. It exists different actors that can be classified in the SCLA model, in this case it has been divided in the Workers, Local Community, Society, Value Chain and Consumers. The indicators have been defined previously associated with the different actors. The values can be numerical (percentage, ratios, relatives, or absolutes) or as affirmative/negative declaration (in the most indicator cases). It has been observed positive SLCA results due the high quantity of indicators with good practises results, also the numerical results reflect a realistic mean in European context maybe with improvement margin in equal opportunities ratios.

3 Conclusions

Currently, the marine industry has a great use, research and evolution potential. This world area plays a key role in climatic stability and must be preserved in terms of environment impact to achieve a sustainable development. For this reason, all the marine human activities and products are under governments and organization environment policies. In this context it arises the ENDURUNS project as mission to create a renewable energy source system capable to performance long endurance sea survey activities. In this article, it has been analyzed the

Table 5. ENDURUNS project SLCA results

ACTORS	CATEGORY	INDICATORS	VALUES	RESULTS
Workers	Freedom of Association	Presence of unions	Yes/No	Yes
		Total number of affiliates https://ilostat.ilo.org/topics/union-membership/	% (people in union/total)	16.70
	Child Labor		Yes/No	No
	Fair Salary	Wage inequality (average salary compared to managers salary)	% (average sakary / managers salary)	66.82
		Average annual wage in the sector	€	41605
		Payment according to basic wage	IMW	Yes
		Compensation for overtime	Yes/No - % vs regular payment	Yes
		Lowest paid worker annual wage	€	24705
	Equal opportunities /discrimination	Employment rates of people with special needs with respect to the total employed people	%	3.56
		Men to women occupation ratio in the company (10 workers)	Ratio	8:2
		Measures to improve gender equality	Yes/No	Yes
		Career Development	Yes/No	Yes
		Men to women executive managers ratio (10 workers)	Ratio	9:1
	Health and safety	Education, training, counselling, prevention and risk control programs in place to assist workforce members (GRI LA8)	Yes/No	Yes
		Presence of a policy concerning health and safety	Yes/No	Yes
		Accident ratio per employee	accidents / year / 1000 workers	0,0097
		Work-life balance	Yes/No	Yes
Local Community	Local employment	Promotion of local employment within the project	Yes/No	Yes
		Percentage of workers who reside in the local community	%	91.3
	Access to material resources	The local community still retain access to raw material extractes	Yes/No	Yes
	Safe and healthy living conditions	Environmental certifications	Yes/No	Yes
		Health and safety impacts bythe activities of the company	Yes/No	Yes
		Community initiatives for improvement	Yes/No	Yes
		Transparency on social/environmental issues	Yes/No	Yes
Society	Product utility	Relevance of the product to the satisfaction of basic needs	Yes/No	No
		Technology used is accesible and affordable for developing countries	Yes/No	No
	Public commitments to sustainability issues	Agreements on sustainable issues	Yes/No	Yes
		Existence of public sustainability reporting	Yes/No	Yes
	Corruption	Legal actions during the assessment period	Yes/No	No
Value chain	Fair competition	Legal actions during the reporting period (as company being membership in alliances behaving in an anti-competitive way)	Yes/No	No
	Respect for intellectual property rights		Yes/No	Yes
	Supplier Relationships	Social criteria implementation in the homologation of suppliers	Yes/No	Yes
Consumers		Health damages in the use of the product	Yes/No	No
		Quality labels	Yes/No	Yes
		Access to objective information	Yes/No	Yes
		Cost of electricity relative to household income significantly differ across populatios served by the utility	Yes/No	No
		End of life - consumer responsibility	Yes/No	Yes

environmental aspects of this system Life Cycle following the ISO guidelines. The main conclusions can be resumed in the following points:

- The purely contaminant substances form the project has been study throughout the Life Cycle Assessment. It is possible to conclude that it exits improvement margin in manufacturing and use stages, using sustainable materials and optimizing the hydrogen energy source extraction.
- The economic aspects involved in this project has been examined in its Life Cycle Cost analysis. Thus, the profitability will depend on the incomes scenario developed. In op-

timistic and average estimations, it is guaranteed the successful project investment at the end-of-life cycle.

- The social impact has been studied applying the Social Life Cycle principles. The model designed for this part has been considered a mean of the different partners of the project. The results show a clear positive impact in social terms; however, it can be improved the discrimination ratios or the product utility for the society.

In summary, the ENDURUNS project Life Cycle impacts are positive in autonomous marine vehicles context and represent a sustainable upgrade in this industry. Also, the novelties implemented in this project can be applied in several systems. As future work, it can be possible to generate the documents to achieve environmental certifications. Also, a most detailed life cycle aspects results report and potential improvements to avoid hotspot detected.

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