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Life cycle assessment of an autonomous underwater vehicle that employs hydrogen fuel cell

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ABSTRACT

In recent years, there has been a significant increase in the adoption of autonomous vehicles for marine and submarine missions. The advancement of emerging imaging, navigation, and communication technologies has greatly expanded the range of operational capabilities and opportunities available. The ENDURUNS project is a European research endeavor focused on identifying strategies for achieving minimal environmental impact. To measure these facts, this article evaluates the product impacts employing the Life Cycle Assessment methodology for the first time, following the ISO 14,040 standard. In this analysis, the quantitative values of Damage and Environmental Impact using the Eco-Indicator 99 methodology in SimaPro software are presented. The results report that the main contributors in environmental impact terms have been placed during the manufacturing phase. Thus, one of the challenges is accomplished, avoiding the use phase emissions that are the focus to reduce nowadays in the marine industry.

Introduction

In recent times, significant advancements have been made in the field of unmanned vehicles known as Autonomous Underwater Vehicles (AUV). Through automation and robotization enhancements, these vehicles have evolved, eliminating the need for human drivers or operators during missions. These innovations have effectively mitigated the risks associated with human submersion. Detailed historical and technical references provide valuable insights and reviews in this domain. [1,2]. The ENDURUNS project is actively pursuing this objective with financial backing from the European Commission under the "Horizon 2020″ program. As such, the project aligns with the broader global efforts focused on ocean exploration and maritime mobility. There are other organisms, e.g., the General Bathymetric Chart of the Oceans (GEBCO) and the International Oceanographic Commission, supporting several research projects and initiatives in this field as "Seabed 2030″, described in reference [3]. Concretely, the ENDURUNS project is focused on the development of a long-endurance and sustainable system for marine and submarine inspections. In this case, the submarine developed by the project has a novel upgrade concerning the current technologies in the field of energy sources. The ENDURUNS AUV develops a modern system based on a hydrogen fuel cell for electric power generation, storing the energy in a battery pack connected to it. This solution represents a considerable evolution in the AUV market [4].

To assess the sustainability and environmental impact of this project, it is necessary to provide a Life Cycle (LC) description and conduct a Life Cycle Assessment (LCA) evaluation. This process considers the regulatory and policy requirements specific to this study. The ISO 14,000 series outlines the key aspects related to LC considerations. The results obtained from this analysis have great applications in the decision-making process to reduce the environmental impact as it is explained in reference [5]. There exist some studies about underwater vehicles with different sustainable motifs. Table 1 shows different works and research lines developed in the last years:

Thus, this article is motivated by these approaches, and it tries to fill the gap in the AUV LCA studies with the mentioned project aim and following a previous draft developed by the authors in reference [12] and offering novel quantitative and qualitative data and results in AUV LCA literature.

The remainder of the paper is organized as follows: Section 1 provides an overview of the current state of the field and the methodology employed in this study. Section 2 offers a comprehensive description of the LCA conducted for the ENDURUNS AUV. Section 3 presents the key findings of the assessment, including an analysis of uncertainties. Lastly, Section 4 summarizes the main conclusions drawn from this research.

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Nomenclature list

GEBCO	General Bathymetric Chart of the Oceans
AUV	Autonomous Underwater Vehicle
LC	Life Cycle
LCA	Life Cycle Assessment
ISO	International Organization for Standardization
GWP	Global Warning Potential
ELCD	European Life Cycle Database
CML	Centrum voor Milieukende Leiden
WCED	World Commission on Environment and Development
CE	European Conformity
EPD	Environmental Product Declaration
UNE-EN	Una Norma Española/European Norm
ILCD	International Life Cycle Data System
DALYs	Disable Adjusted Life Years
PDFs	Potentially Disappeared Fraction*m^2year
MJ	Mega Joules
PAF	Potentially Affected Fraction
Pt	Eco Points

Table 1
Autonomous Underwater Vehicles LCA studies.

Study	Methodology	Year	Reference
It develops an LCA for different Autonomous Underwater vehicle power options.	Eco-indicator 99 with Ecoinvent database.	2006	Jan Verdaasdonk et al. [6]
It evaluates different fuel chain LCA in marine vehicles.	GWP100 with ELCD database.	2011	Selma Bemgtsson [7]
It performs a comparative LCA of different clean fuels for marine vehicles.	CML 2001 with Ecoinvent database.	2018	Yosuf Bicer and Ibrahim Dincer [8]
The objective of this study is to conduct an LCA for marine vessels to determine the most suitable propulsion system.	CML 2016 with GaBi database.	2018	Byongug Jeong et al. [9]
This study employs LCA analysis to evaluate and quantify the environmental impact associated with constructing and recycling steel hulls.	CML with Ecoinvent database.	2020	Mehmet Önal et al. [10].
The sustainability of manufacturing aluminum/ steel welding in marine applications is analysed through LCA.	ILCD 2018 99 with Ecoinvent database.	2022	Guido Di Bella et al. [11].

Methodology fundaments

Nowadays, the sustainability analysis and environmental impact of the products are taking great importance due to different indicators shown in reference [13]. The first definition of the LC concept appears in 80s decade in the “Sustainable Developed” book published by the official World Commission on Environment and Development (WCED) [14]. Since then, it has been developing intensive work in this field to optimize the industrial processes for environmental preservation. The institutions and governments are regulating tougher policies in terms of contamination [15]. The most commonly measured factor is the greenhouse gas emissions regulated and focused on the last Climate Conventions and established in the Kyoto Protocol (1997), it was deeply analysed in reference [16].

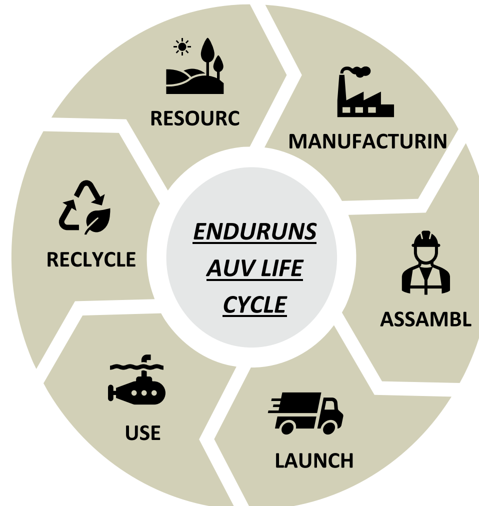

Fig. 1. ENDURUNS AUV LC Stages.

The LC study can be conducted at various levels of complexity, contingent upon the stages encompassed within the analysis. A comprehensive LC entails examining the entire lifecycle of the product, from its initial creation to its eventual dismantling and recycling, thereby completing the ecological loop commonly referred to as "cradle to cradle." Further details on this concept can be found in the provided reference [17]. Fig. 1 illustrates the graphical representation of the LC analysis conducted for the ENDURUNS case study involving the AUV. This analysis comprises six distinct stages. Nevertheless, it is worth noting that there are alternative approaches available to streamline the study, such as the cradle-to-gate approach, which specifically focuses on the manufacturing process. A concise summary of this approach is provided in the reference. [18].

The impact of a product on contamination is evaluated based on the emissions and environmental damage generated throughout its LC. In Europe, certifications such as the European Conformity (CE) and Environmental Product Declaration (EPD) are employed. The EPD certificate offers valuable, verified, quantitative, and comparable data regarding the environmental impact of a product [19]. The LCA framework consists of four interlinked phases: Phase 1 - Goal and Scope Definition, Phase 2 - Inventory Analysis, Phase 3 - Impact Assessment, and Phase 4 - Interpretation [20]. These phases will be developed in this article and applied to the case of the study of ENDURUNS AUV. The results obtained from the LCA study will apply to product sustainability improvements, green marketing and strategic or to comply policies referenced in [21].

ENDURUNS AUV LCA

The LCA framework outlines four distinct phases that are essential for conducting a comprehensive study, although it is important to note that this is a theoretical assumption. For the UAV’s LC, specific stages such as assembly, launch, and product use contribute collectively to its environmental impact. In contrast, the AUV is assessed by considering its components separately. Therefore, the simulation case establishes the basis for a cradle-to-grave analysis.

Objective, scope and definition

Phase 1 of the LCA entails establishing the objectives, scope, and context of the study. In the case of the ENDURUNS AUV, the LCA involves a comprehensive analysis of the LC processes and sub-processes, extending from manufacturing to product retirement. The scope of this study encompasses the entire Cradle to Grave LC stages, including the manufacturing processes for each AUV component, the assembly

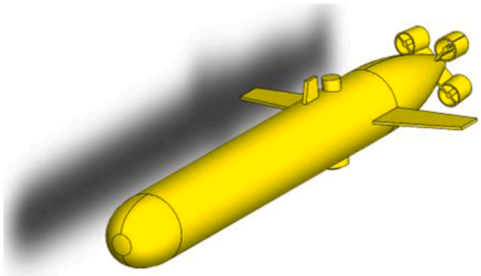

Fig. 2. ENDURUNS AUV Prototype.

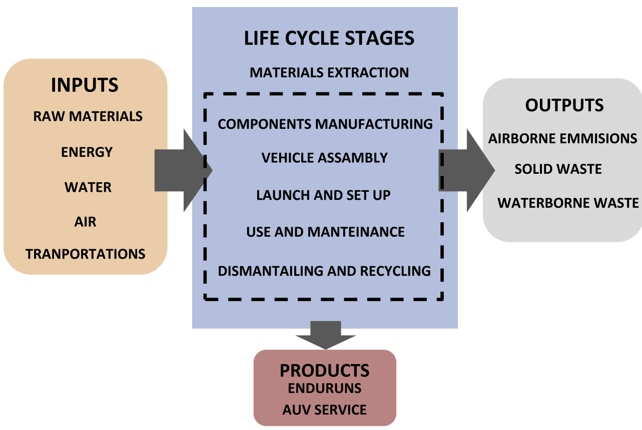

Fig. 3. ENDURUNS AUV Inventory Analysis Flowchart.

process, launch and setup operations, implications during the AUV's lifespan, and ultimately, the end-of-life dismantling process [22].. The insights derived from the project's latest findings have been considered to develop this study. The examination of the UAV components stands out as the most involved and intricate subprocess under evaluation. Fig. 2 displays the prototype of the UAV.

The modular nature of the UAV is evident, with distinct components dedicated to propulsion, mapping, energy, and buoyancy. This configuration enhances the versatility of the UAV, enabling future modifications to accommodate new mission requirements. Such adaptability represents a favourable aspect in terms of sustainability. Furthermore, the model's outcomes prove valuable for conducting an environmental analysis of the project, facilitating the evaluation of emissions and waste generation. These contributions aid in achieving sustainable optimization, as proposed in the reference [23].

Inventory analysis

This phase aims to summarize and quantify the inputs and outputs associated with the LC processes and stages. These flows encompass raw materials, energy consumption, and waste generation throughout the product's LC, as detailed in the provided ref. [24]. This part of the study needs a great volume of data. SimaPro is an environmental impact auditory software developed by PRé Sustainability, a consultancy enterprise for the Netherlands funded in 1990 by experts in this field. SimaPro software provides a dedicated workspace for conducting this process, allowing for efficient development and storage of all relevant information using a comprehensive global environmental database. The system boundary of the product is depicted by a square dotted line, excluding materials extractions. Each process identified in the product's LC needs to be integrated into the software model. The inventory can be divided into distinct processes, incorporating individual flows within each of them. Fig. 3 shows a conceptual map of the LCA inventory for this case of study.

The system boundary for the product is delineated by a square dotted line, excluding materials extraction. The software model needs to incorporate each previously defined process of the product's LC. The inventory can be partitioned into various processes, with the ability to account for individual flows within each of them.

Table 2 shows a draft of the inventory analysis performed for this study. It should be noted that the materials extraction subprocess has been included in the components manufacturing flow as it is made in [25]. The inputs and outputs of each process have been filled out using the database provided by the software, in this case, the international Ecoinvent database support described in [26].

Impact assessment

In accordance with the UNE-EN-ISO 14,040:2006 guidelines, several methodologies have been developed for assessing environmental impact. Some of the most widely recognized methodologies include Recipe, IMPAC 2002+, Eco-Indicator 99, EDP, and ILCD. [27]. Most of these methods have been developed by PRè-Sustainability corporation in collaboration with different European universities and institutes. The authorship of them has as its main reference the eco-designer and pioneer Mark Goedkoop, responsible for the dissemination and development of this ground since the '90 s [28]. In this study, the Eco-Indicator 99 method was employed to assess the ENDURUNS AUV case. This methodology, developed by Mark Goedkoop in collaboration with the PRè-Consultants team, addresses the challenges associated with the weighting step in the ISO 14,040 standard [29]. The Eco-Indicator 99 is an endpoint approach and divides the environment impact categories into three groups of damage with each one defined and

Table 2
ENDURUNS AUV Inventory Resume.

	INPUTS						OUTPUTS		
PROCESSES	SUBPROCESSES	RAW MATERIALS	ENERGY	WATER	AIR	TRANSPORTATION	AIRBORNE	SOLID	WATERBORNE
Manufacturing	AUV Components	X	X	X	X	X	X	X	X
Vehicle Assembly	AUV Assembly	X	X	X	X			X	X
	Suppliers Shipping					X	X		
Set-Up	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

Table 3
Eco-Indicator 99 results for ENDURUNS AUV.

DAMAGE CAT.		Human Health (DALY)					Ecosystem Quality (PDF*m^{2}year)				Resources (MJ)	
IMPACTS		Carcinogens	Resp. Organics	Resp. Inorganics	Climate Change	Radiation	Ozone Layer	Ecotoxicity*	Acidification	Land Use	Minerals	Fossil Fuels
PRODUCT LIFE CYCLE PROCESSES	Manufacturing	4,23E-3	2,13E-6	3,05E-3	4,13E-4	4,88E-6	1,99E-7	1,02E4	52,9	1,35E3	564	1,72E3
	V. Assembly	1,82E-4	5,37E-8	1,13E-4	3,64E-5	6,88E-7	1,15E-8	495	3,05	59,2	13,3	146
	Set-Up	4,57E-6	1,95E-8	7,84E-5	2,55E-5	7,16E-7	3,05E-8	11,6	1,97	1,21	0,29	82,1
	Launch	2,08E-5	7,64E-7	1,45E-3	1,05E-4	9E-7	8,89E-8	304	60,3	8,42	3,87	821
	Use	3,45E-4	4,48E-6	1,17E-3	6,16E-4	5,15E-6	9,25E-7	693	31,1	160	33,9	1,42E4
	Maintenance	1,75E-5	5,73E-7	1,08E-3	7,65E-5	5,99E-7	6,31E-8	231	45,1	6,96	2,99	609
	Dismantling	−4,4E-4	2,56E-7	6,51E-4	3,51E-5	2,43E-7	2,9E-8	806	20	1,93	−97	287
	Recycling	2,61E-4	−5,8E-8	−5,2E-5	1,56E-5	1,68E-7	1,6E-8	2,62E3	−0,6	3,28	5,24	39,3
	PARTIAL SUM	4,62E-3	8,21E-6	7,53E-3	1,32E-3	1,33E-5	1,36E-6	1,54E4	214	1,59E3	526	1,79E4
	TOTAL	**0,0135**	**9590**	**17,526**								

* Measured in Potentially Affected Fraction (PAF) instead of PDF, assuming PDF=0,5PAF.

normalized units given in brackets: Human Health (Disable Adjusted Life Years or DALYs), Ecosystem Quality(Potentially Disappeared Fraction*m^{2}year or PDFs) and Resources (Megajoules surplus energy or MJ), detailed in [30]. Table 3 shows the numerical results obtained in the mentioned unit's terms. The results are presented detailing all the damage categories and finally doing the total sum for each group of impact.

Table 3 shows the contribution of each product LC process damage evaluation. It is possible to observe that a great amount of the total corresponds with the product manufacturing process. It also notes that the Dismantling and Recycling processes present negative outcomes in some impact categories, this is due to the beneficial character of these processes about each associated methodology aspect. For a deeper and more meaningful analysis, it will be proper to evaluate each damage impact category to detect critical processes in each area. For example, if the focus is the carcinogen's impact, it is possible to observe that the most harmful process is Manufacturing, with an order of magnitude. On the other hand, the

The dismantling process reports a negative value, this fact indicates a positive effect of this process on the carcinogens index in environmental profits. This negative contribution is clearer exposed in the following Fig. 4 in percentage terms.

SimaPro software also provides a visually intuitive graphical representation of the results obtained from the LCA. [31]. Fig. 5 allows to identify each process's contributions in terms of percentage and weighting. The "x" axis represents the Eco-Indicator 99 damage categories and the "y" axis represents the percentage in the first case and Eco Points or single score (Pt) in the second case with the same color code as Fig. 4.

It is possible to observe that the main contribution for Human Health and Ecosystem Quality categories is the AUV Manufacturing for a) and b) with around 57%,73%,350Pt and 170Pt respectively, while the most contributively process in terms of Resources Impact is the AUV Use with around 77% and 376Pt. Another important contribution in the case of Human Health is the Launch Process with around 12% and 72Pt, due to the cargo ships [32] and trucks [33] employment with the corresponding high CO2 emissions.

Interpretation

The objective of this phase of the LCA is to summarize the findings and outcomes of the methodology employed. By interpreting these values, it becomes possible to analyze the level of product contamination. In this particular instance, a preliminary and approximate assessment of the ENDURUNS project AUV is obtained.

In this case, there are some tools included in the software to extract relevant information from the product LCA. One of them is the Sankey Diagram or processes tree, with this representation it is possible to visualize with a "cut off" filter the contribution of each process for the final product. In this case, Fig. 6 shows the higher than 4% contribution processes. It observes that the main contributions correspond with the AUV Manufacturing and the Use processes, reaching around 80% of the total. Thus, these processes should consider carefully to make changes to reduce the environmental impact, if necessary.

In environmental terms, it is possible to extract interesting data from this study. As occurs in other cases as the car tires, exposed by K. Piotrowska et al. in [34], it is possible to do an uncertainty analysis with Montecarlo methodology [35].

Fig. 7 shows the outcomes conducted to examine the uncertainties associated with the ENDURUNS AUV LC processes. The average value obtained is 1810 Pt. The other parameters characterizing the distribution include a Median of 1800 Pt, a Standard Deviation of 132 Pt, and a Coefficient of Variation of 7.3%. The dispersion of the final results demonstrates a relatively minor diversification, suggesting that the Median value effectively represents the average level of the environmental impact encompassing the entire ENDURUNS AUV LC.

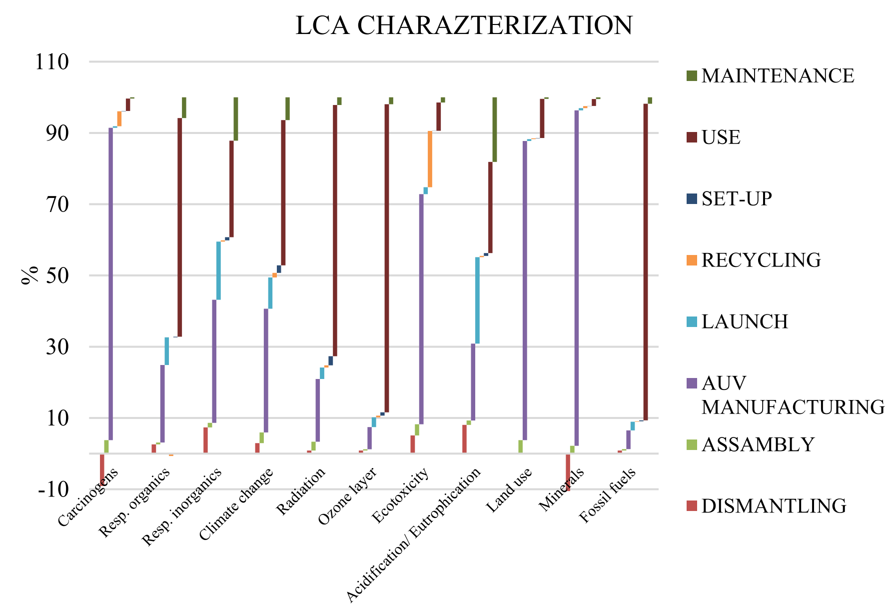

Fig. 4. LCA Characterization of ENDURUNS AUV processes.

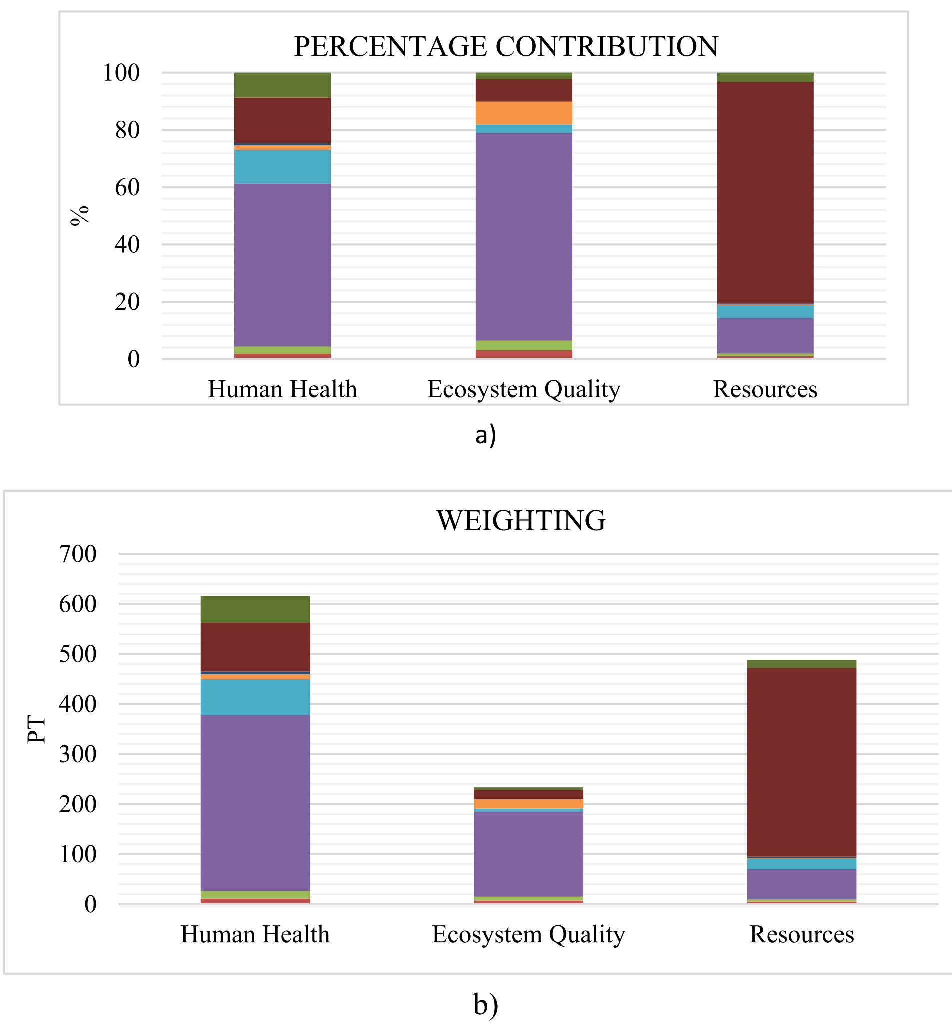

Fig. 5. Eco-Indicator Bar Chart Results: a) Percentage Contribution and b) Weighting.

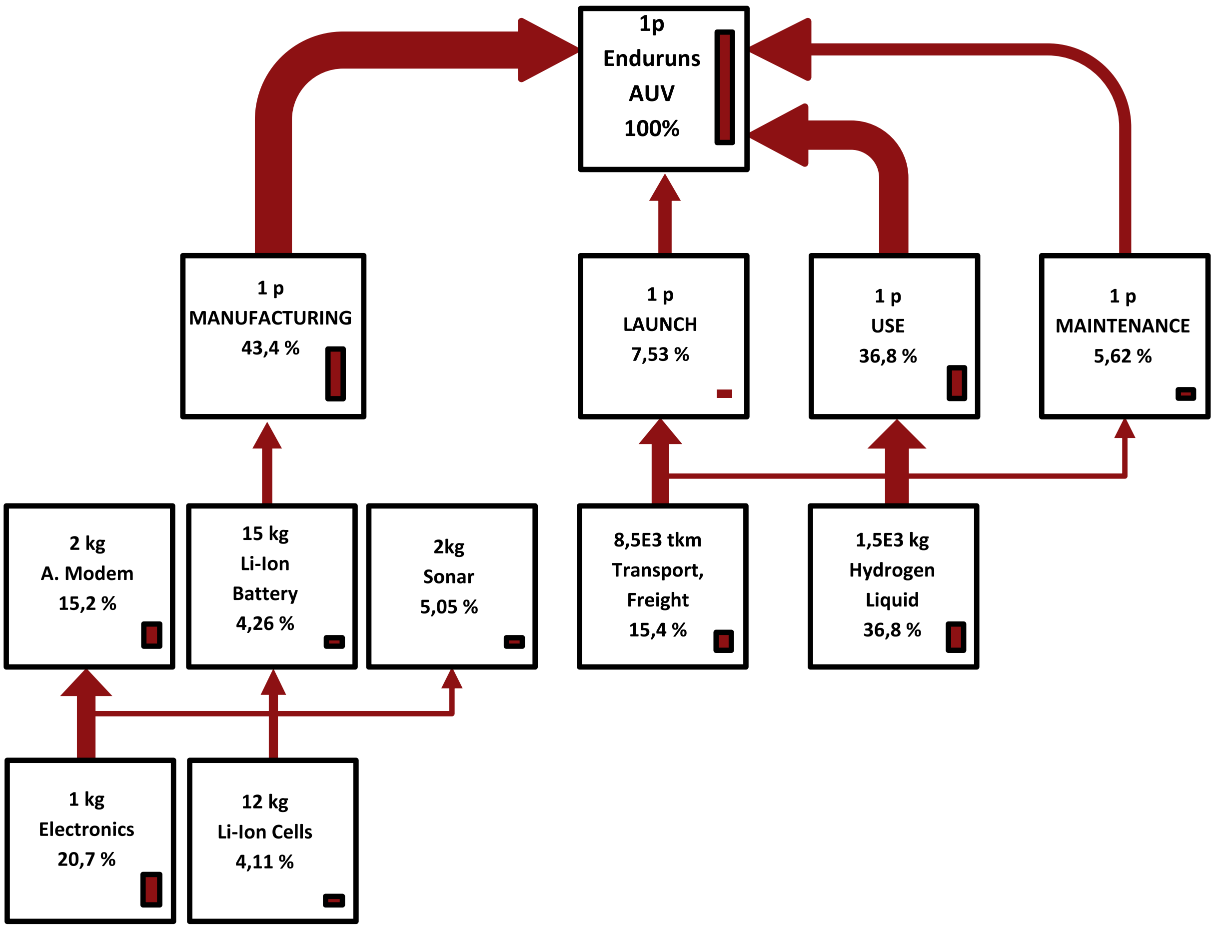

Fig. 6. ENDURUNS AUV LCA Sankey diagram.

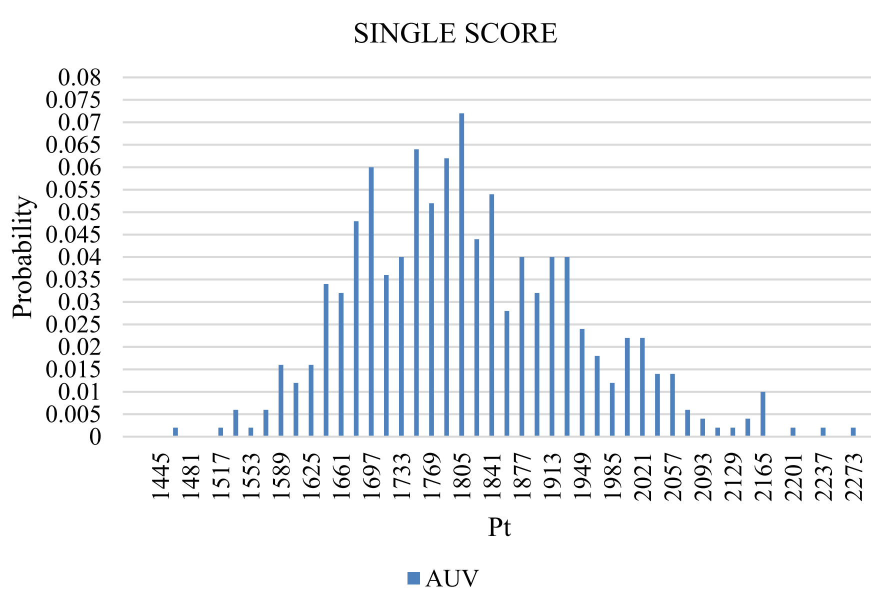

Fig. 7. Uncertainty Analysis for ENDURUNS AUV LC study.

The findings from the comprehensive LCA study suggest the following summary for the uncertainty analysis: Based on the collected data, it can be inferred that the eco-points value for the complete LC of an AUV, considering all the processes 153 Pt. The associated standard deviation is 132 Pt, indicating a 95.5% probability (±2 σ) that the eco-points value for the ENDURUNS AUV will fall within the range of 1590 to 2110 Pt.

Conclusions

Research initiatives like the ENDURUNS project necessitate a comprehensive Life Cycle Assessment to ensure their eco-design focus and evaluate their environmental impact. The autonomous underwater vehicle developed within the ENDURUNS project incorporates a hydrogen fuel cell as its energy source. For this reason, the main impacts come from the manufacturing phase as has been proved. The analysis developed in this paper is focused on the cradle-to-grave processes of the ENDURUNS Autonomous Underwater Vehicle Life Cycle as the project reports and achievements. The main conclusions are resumed in the following points:

- The numerical results of the Damage Categories enable the identification of the highest values for each environmental impact and life cycle process. This helps in detecting the most significant impacts throughout the life cycle of the product. In this case, the partial sum reveals that the Respiratory Inorganics (Human Health) with 7,53E-3 DALYS, the Ecotoxicity (Ecosystem Quality) with 1,54E4 PDF*m2year and the Fossil Fuels (MJ) with 1,79E4 MJ are the most critical indicators.
- The contribution of each process of the life cycle is measurable. It has been obtained percentage and weight contributions of a graphical representation with bar charts and the Sankey diagram. This analysis reports the greatest influence of the AUV manufacturing process achieving 43,3%, followed by 36,8% from the Use contribution over the total product life cycle.
- According to the uncertainty analysis simulation, it is reported successful results for the ENDURUNS LCA study validation with a low coefficient of variation.

This analysis reports the greatest influence of the AUV manufacturing process, followed by the Use contribution over the product life cycle. However, this theoretical study must be contrasted and monitored during the project life cycle to guarantee the correct measurements in terms of sustainability according to the legislative restrictions. This work has a certain improvement margin due to the theoretical assumptions of some data and processes. For future work, it can be proper to develop a precise assessment of the definitive vehicles and physical examinations to certify the measurements.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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