LIFE CYCLE ASSESSMENT AND CIRCULAR ECONOMY INDICATORS TO DESIGN SUSTAINABLE ELECTRIC OUTBOARDS: RESULTS FROM WORKSHOPS WITH INDUSTRIAL EXPERTS

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ABSTRACT

To help industries in their sustainable and circular transition from internal combustion engine production to electric motor production, the deployment of (i) a sound environmental impact assessment methodology, such as life cycle analysis, coupled with (ii) Design for Re-X tools, such as circularity indicators, is instrumental. To demonstrate the industrial relevance and complementary of both approaches, two consecutive workshops are conducted with a major original equipment manufacturer of recreational boats and their associated engines. On this basis, two circularity indicator-based tools were used to quantify and enhance (i) the circularity potential of the electric outboard as a whole, and (ii) the circularity performance of the two most impactful components, based on the LCA results: the electric motor unit and the lithium-ion battery pack. In all, the practice sessions supported the generation of strategic and operational ideas to improve the circularity of the electric outboard. As the industrial participants found both frameworks easy to use and efficient, all the details and resources used to conduct, replicate, or adapt such workshops in other industrial contexts are shared.

Keywords: Sustainability, Circular economy, Design for X (DfX)

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1 INTRODUCTION

While recreational boating is increasing in popularity worldwide, it raises several issues regarding pollution management, aquatic ecosystem preservation, and waterway access (Hemez et al., 2020). To address these challenges, the design of new circular and sustainable electric outboards is key to operating recreational boats that respect nature and aquatic ecosystems. Electric boat technology can actually be a sustainable alternative to conventional gasoline-powered boats, by: reducing the use of oil and fossil fuels, mitigating greenhouse gases (GHG) emissions, decreasing the magnitude of vibrations and generated noises, ease of maintenance, and optimized efficiencies (Del Pizzo et al., 2010, Hemez et al., 2020; Minami et al., 2010).

At the same time, transitioning to circular economy practices can support companies in the achievement of their sustainable development goals (Schroeder et al., 2019). In particular, the integration of circular economy strategies during the product design and development process can significantly positively impact circularity and sustainability performance (Diaz et al., 2022).

Through the sustainable electrification of recreational boats in a circular economy trajectory, this project aims to support boat makers in contributing to the conservation and sustainable use of the oceans, seas, and marine resources. Overall, it aims to contribute to rethinking, building, and optimizing a circular supply chain in the recreational boat industry.

More specifically, the present work aims to identify and quantify opportunities to design electric outboards for Re-X (i.e., reuse, remanufacturing, recycling). In this line, the two complementary research questions (RQs) addressed in this paper are: (RQ1) How to quantify the circularity potential and ecological performance of an electric outboard? (RQ2) Which designs for Re-X strategies and mechanisms are the most commendable to close the loop sustainably?

2 MATERIALS AND METHODS

To help industries in their sustainable and circular transition (e.g., from internal combustion engine production to electric motor production), we argue that the deployment of a sound environmental impact assessment methodology, such as life cycle analysis (LCA), coupled with design for Re-X tools, such as circularity indicators (CI), can be instrumental.

To demonstrate the industrial relevance and complementary of both approaches, two consecutive half-day workshops are conducted with a major original equipment manufacturer of recreational boats and their associated engines. Such workshops, conducted in industrial environments, have proven to be helpful in generating eco-innovations (Saidani et al., 2016) or in evaluating the circularity performance of products (Saidani et al., 2019a) in a time-efficient manner. Here, the originality lies in the interrelations between life cycle assessment and circular economy indicators, as well as the application of the approach to an industrial case study with a working group composed of several industry experts.

These workshops are indeed designed and operated by two sustainable design experts in industrial engineering and were attended by the principal industrial stakeholders and actors in the design and development of electric outboards, including, e.g., two materials engineers, the technical product lead, the remanufacturing general manager, and the director of sustainability engineering programs.

The electric outboard used for this project is made of three main sub-assemblies: the electric motor unit, the lithium-ion battery pack, and the propeller. Its specific characteristics are the following: 15-inch shaft outboard motor of one horsepower (1 hp). This electric outboard is, in theory, more than 90% recyclable. The complete bill of materials (BoM), usage data, and maintenance information have been provided by the original equipment manufacturer.

2.1 Workshop #1 on life cycle analysis (LCA)

The first half-day session, focused on LCA, aimed to showcase how to calculate the environmental impact of a new electric outboard (the Avator 1hp), in order to identify environmental hotspots and quantify potential impact savings (e.g., from material alternatives or circular economy loops).

LCA is a tool to determine the environmental impacts of a product, process, or activity throughout its life cycle (ISO 14040, 2016). Though commonly used to evaluate environmental impacts, LCA is a

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valuable decision-making tool. It can be used to compare competitive systems, generate knowledge for environmental innovation, and identify environmental hotspots, i.e., the sub-assemblies, parts, components, or materials of a product that contribute the most to its footprint.

A full LCA can take, in general, months to be completed even for an experienced professional, as pulling together data can be time-consuming and costly, and compiling life cycle inventory (LCI) is one of the biggest obstacles to the wide adoption of LCA (Bhander et al., 2003; Reap et al., 2008; Cerdas et al., 2017). Therefore, the LCI has been modeled and pre-filled in the software OpenLCA 1.10 (Ciroth, 2007; Ciroth et al., 2019) and in an *ad hoc* Excel-based calculator customized for the original equipment manufacturer (OEM) (including three simple input tabs: BoM, maintenance, usage) to save time and focus on the LCA methodology, results, and interpretations. The database used for emission factors and impact numbers is ecoinvent 3.7 (Wernet et al., 2016), and the methodology for life cycle impact assessment (LCIA) is the ReCiPe (H) Midpoints 2016 (Huijbregts et al., 2016).
As most of the industrial participants (listed in Table 1) were not familiar with LCA, the first half-day session started with an introduction to the LCA methodology, following the four stages of the ISO 14040 (2006) standard, namely: (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact assessment, and (iv) interpretation. Next, an illustrative example was showcased, performing an LCA on one of their gasoline-powered recreational boats and focusing on the outcomes (i.e., the specific impact numbers for this boat). Then, the complete LCA process was applied to the new electric outboard, from goal and scope definition to results interpretation with the industrial stakeholders (see section 3), i.e., with the engineers and managers working on this electric outboard. The workflow of the LCA session is depicted in Figure 1.

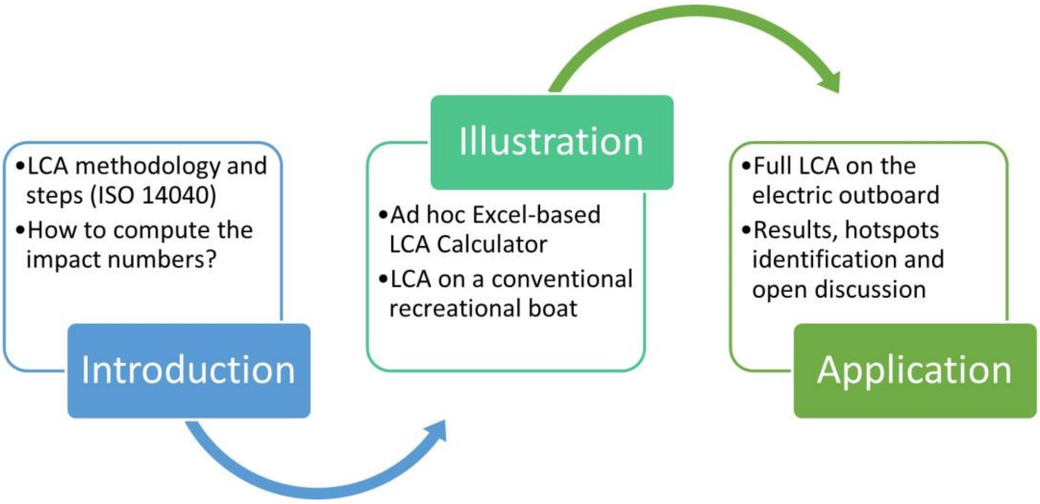

Figure 1. Synopsis of the life cycle assessment workshop

2.2 Workshop #2 on circularity indicators (CI)

On this basis, during the second half-day session, two circularity indicator-based tools were used to assess (i) the circularity performance of the electric outboard as a whole with the Circular Economy Indicator Prototype (CEIP) (Cayzer et al., 2017), and (ii) the circularity potential of two critical components, the electric motor unit, and the lithium-ion battery pack, using the Circularity Potential Indicator (CPI) (Saidani et al., 2017). The two specific CI have been pre-selected, following the taxonomy of circular economy indicators and its associated selection tool (Saidani et al., 2019b), to fit with the industrial requirements of this project (i.e., intrinsic circularity performance, time-efficient, easy to use and understand, even by non-circular economy experts). Also, these two indicators and their associated Excel-based tools have already demonstrated their relevance in supporting the ideation of eco-improvement based on their outputs (Saidani et al., 2021). They particularly allow capturing several Re-X strategies at different levels.

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Table 1. List of industrial participants, by circularity indicators

Circularity Potential Indicator (CPI)	Circular Economy Indicator Prototype (CEIP)
Director of Sustainability Engineering Programs	Chief Sustainability Officer
General Manager of Remanufacturing	Advanced Engineering Director
Product Technical Lead	Research & Innovation Lab Director
Materials Engineer	Materials Engineer
Sustainability Intern	Sustainability Intern
Engineering Co-op (cooperative education)	

First, an overview of the different methods and tools to design for Re-X was given (Garcia-Saravia Ortiz-de-Montellano and van der Meer, 2022) before focusing on the existing tools to quantify the circularity performance of products. Then, the industrial participants were split into two groups, as listed in Table 1, to apply one of the two circularity indicators on the electric outboard. Based on the results of their assessment (see section 3), they came up with several solutions, including design ideas and business strategies to increase the circularity performance of their newly developed electric outboard. The workflow of the CI session is depicted in Figure 2.

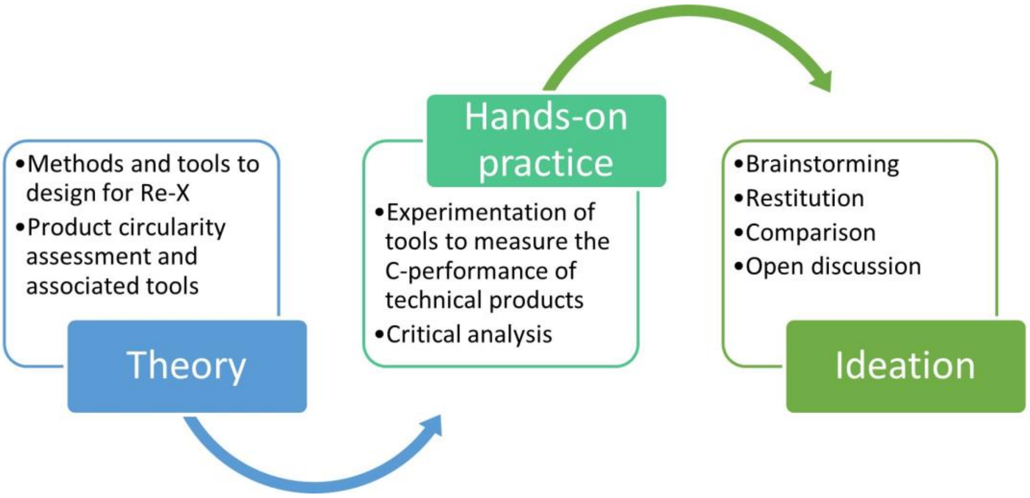

Figure 2. Synopsis of the circularity indicators workshop

3 RESULTS AND INTERPRETATIONS

3.1 Life cycle impact assessment

The aim of this LCA is to quantify the environmental footprint of a new electric outboard (the 15-inch Avator 1hp, see CAD model at the top left corner of Figure 3) in order to identify environmental hotspots and estimate potential savings (e.g., from material alternatives or design for Re-X strategies). The functional unit, used as a baseline for comparison, is defined as follows: manufacture and operate one electric outboard of one horsepower for recreational boating during one lifetime, i.e., 35 hours a year for 15 years. The complete scope and system boundaries of this LCA are illustrated and summarized in Figure 3. Note that the end-of-life (EoL) phase is not included in the current scope of the LCA mainly because the EoL of this electric outboard for recreational boats is currently unknown. Although different scenarios could have been imagined to fill that gap on the LCA, the decision was to not alter the LCA results with uncertainty and to focus on the accurate dataset provided by the OEM, in order to generate meaningful insights regarding the design, usage and maintenance phases, as discussed hereafter. Additionally, to fill this gap regarding the EoL of the electric outboard, two circularity indicators are being used to assess the circularity potential of the electric outboard, as it is currently designed, and to identify possible improvements, e.g., in terms of design, materials, business models, to *in fine* maximize its circularity.

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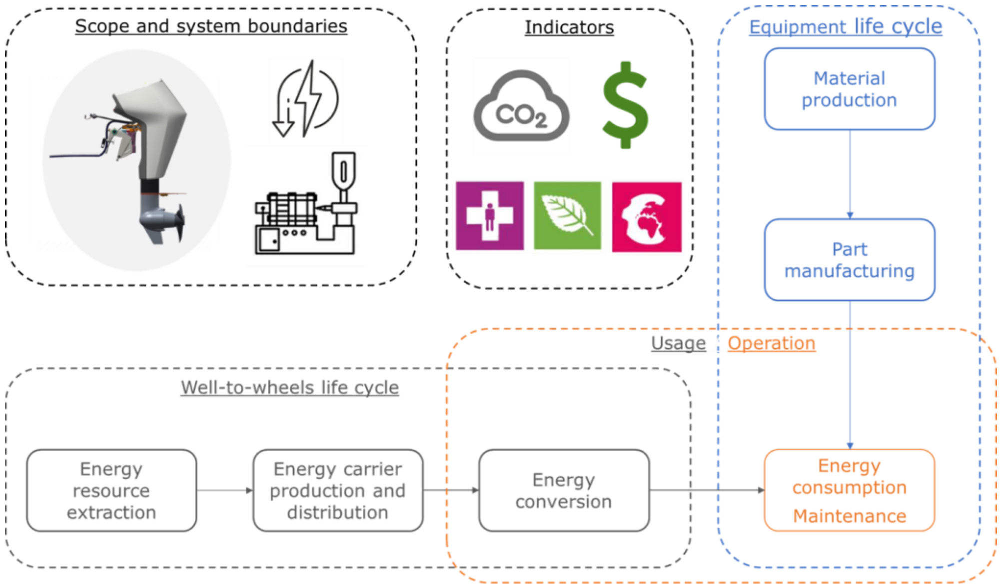

Figure 3. Scope and system boundaries of the LCA

Regarding the bill of materials and usage profile, primary industrial data provided by the OEM have been used. It includes 846 unique parts distributed in 9 sub-assemblies for a total of 28 kg. Regarding the manufacturing processes, secondary data from ecoinvent 3.7 have been used, i.e., average industrial values for metal working and injection molding. Regarding electricity production and consumption, the US average mix has been used. The ReCiPe (H) Midpoints 2016 LCIA methodology has been deployed to compute the impact numbers. While the results from the 18 Midpoints Indicators have been rapidly displayed during the workshop, the focus was made on the global warming potential indicator, in alignment with the company's strategy to decrease its carbon footprint. The hotspot analysis is illustrated in Figure 4, showing the relative contributions of the life cycle stages to the global warming potential (GWP). The two most impactful subassemblies are the electric motor unit and the lithium-ion battery pack.

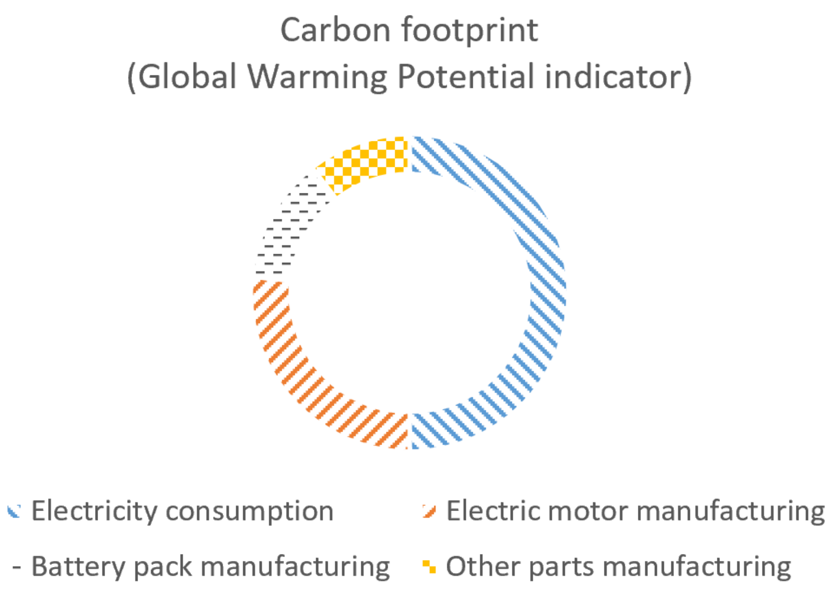

Figure 4. LCA results, global warming potential distribution

The LCA results showed close to an equal distribution of carbon emissions allocated between the manufacturing phase and the usage phase, highlighting both the importance of Re-X solutions (such as increased recycled content or remanufacturing) and the efficiency of the electric motor unit and associated battery pack.

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3.2 Circularity performance

With that background, the industrial participants, split into two working groups, were asked to evaluate the circularity performance of the electric outboard using two complementary circularity indicators. The first working group used the Circular Economy Indicator Prototype (CEIP) to assess the circularity performance of the electric outboard at a full product level. The second working group used the Circularity Potential Indicator (CPI) to evaluate the circularity performance of the two most impactful subassemblies: the electric motor unit and the lithium-ion battery pack.

The CEIP includes 15 questions that intend to evaluate to what degree the product fosters the circular economy principles throughout its different lifecycle stages. The CEIP results are captured in Figure 5. The circularity performance of this product is categorized as "good," with a circularity score of 43% (see Figure 5). Note that the “scored” points correspond to the actual performance of the product being evaluated, while the “available” points correspond to the total number of points that can be attributed to a given product. In the present case, the electric outboard “scored” 65 points out of the 152 points “available” in the CEIP tool, which corresponds to a circularity score of 43%. The design phase of the lifecycle obtained a score of 10 out of 27 because the electric outboard is lighter than the previous version (i.e., its gasoline counterpart) and contains a certain amount of recycled material. The manufacturing phase did not add any points to the circularity performance because, as of now, no renewable energy has been used in the manufacturing process, and there is no recovery treatment for the industrial solid waste generated. Regarding the commercialization aspect, the three additional points only come from the packaging which is made from multiple recyclable materials. On the other hand, the product guarantee does not cover its entire lifetime, and the product cannot be accessed through a rental scheme. During its use phase, the product can be maintained and/or repaired nationwide by specialist firms. Last but not least, at its end of use, a take-back scheme with an incentive is planned to be provided by the retailer.

3 RESULTS

Product Rating	Product Ranking	Points	
		Scored	Available
43%	Good	65	152

Lifecycle	# Questions	Scored	Available	Rating	Ranking
Design/Redesign	3	10	27	37%	Fair
Manufacturing	2	0	25	0%	Poor
Commercialisation	3	3	30	10%	Poor
In Use	4	17	35	49%	Good
End of Use	3	35	35	100%	Excellent
TOTAL	**15**	**65**	**152**	**43%**	**Good**

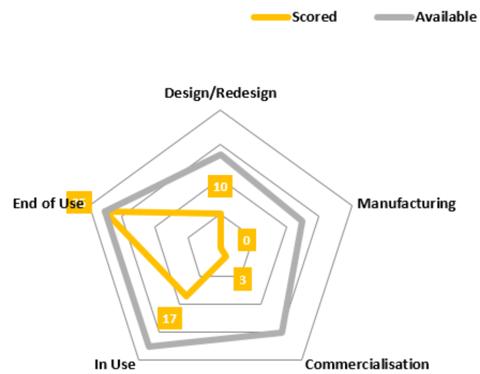

Figure 5. Results of the circular economy indicator prototype for the electric outboard

The CPI is computed through a guided questionnaire of twenty attributes (ATT#) impacting the circular economy performance of a given product, component, or subassembly, following the four building blocks (BB#) of the circular economy defined by the Ellen MacArthur Foundation, namely: (i) circular product design, (ii) new business models, (iii) reverse cycles, and (iv) enablers and favorable system conditions. The overall results of the CPI, applied to the electric motor and lithium-ion battery, are displayed in Figures 6 and 8, respectively. While both subassemblies share a circularity score of the same order of magnitude (47% for the electric motor unit, and 55% for the lithium-ion battery pack), the lithium-ion battery seems more circular ready to go through reverse cycles at its end of use (19.6 out of 25), compared to the electric motor unit (8.75 out of 25). The details of the scores of BB#1 (Circular Product Design) for both subassemblies are given in Figures 7 and 9.

The CPI provides practical directions for improving and monitoring the circularity performance of the key components of products, associated design practices and business strategies. In fact, the breakdown of the score for the building block BB#1 (Circular Product Design) allows industrialists to identify what could be modified, e.g., in terms of material selection, subassembly architecture and connection types, to augment the circularity potential of the product.

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Circularity Performance Indicator *Unlock the Circularity Potential of your Product*	Circularity Score of the Motor = (out of 100)	47.23
BB#1 - Circular Product Design		13.89
BB#2 - New Business Model		7.50
BB#3 - Reverse Cycles		8.75
BB#4 - Favourable System Conditions		17.08

Figure 6. Results of the circularity potential indicator for the electric motor unit

Circularity Performance Indicator *Unlock the Circularity Potential of your Product*	Circularity Score of the Motor = (out of 100)	47.23
BB#1 - Circular Product Design		13.89
ATT#1 - Materials selection and combination compatibility		2.22
Number of differents materials	More than 10	0.00
Technical recyclability of materials combinaison	High	5.00
Material contamination (coating, paints, and material mixing)	Medium	1.67
ATT#2 - Modular product design, adaptability and flexibility		1.67
Is the product contained standardised components	Partly	1.67
Has the product being design with a modular mindset	Partly	1.67
ATT#3 - Design for disassembly and easy end-of-life sorting		4.17
Handling and manoeuvrability of the product (for a single user)	Easy	5.00
Number of different distinct components (regarding the size of the product)	Few	5.00
Joints & connections numbers (regarding the size and number of components)	Few	5.00
Joints & connections types	Dismountable assembly	5.00
Joints & connections accessibility	Partly visible	1.67
Disassembly cost and time (regarding value of the product)	Low	5.00
Tools required for disassembly	Simple or standard tool	2.50
ATT#4 - Design for upgradability		2.50
Possible options of upgradability	Possible	2.50
ATT#5 - Design for maintainability and longevity		3.33
Wear and tear indicator or information	No	0.00
Possibility of maintenance and repair	Yes	5.00
Accessibility, visibility, reachability and identifiability of key components	Easy for a non-specialist	5.00

Figure 7. Breakdown of the circular product design score for the electric motor unit

Circularity Performance Indicator *Unlock the Circularity Potential of your Product*	Circularity Score of the Battery = (out of 100)	55.04
BB#1 - Circular Product Design		11.43
BB#2 - New Business Model		5.00
BB#3 - Reverse Cycles		19.58
BB#4 - Favourable System Conditions		19.03

Figure 8. Results of the circularity potential indicator for the lithium-ion battery pack

Circularity Performance Indicator *Unlock the Circularity Potential of your Product*	Circularity Score of the Battery = (out of 100)	55.04
BB#1 - Circular Product Design		11.43
ATT#1 - Materials selection and combination compatibility		0.00
Number of differents materials	More than 10	0.00
Technical recyclability of materials combinaison	Low	0.00
Material contamination (coating, paints, and material mixing)	High	0.00
ATT#2 - Modular product design, adaptability and flexibility		1.67
Is the product contained standardised components	Partly	1.67
Has the product being design with a modular mindset	Partly	1.67
ATT#3 - Design for disassembly and easy end-of-life sorting		3.93
Handling and manoeuvrability of the product (for a single user)	Easy	5.00
Number of different distinct components (regarding the size of the product)	Few	5.00
Joints & connections numbers (regarding the size and number of components)	Few	5.00
Joints & connections types	Dismountable assembly	5.00
Joints & connections accessibility	Hidden	0.00
Disassembly cost and time (regarding value of the product)	Low	5.00
Tools required for disassembly	Simple or standard tool	2.50
ATT#4 - Design for upgradability		2.50
Possible options of upgradability	but not designed for it	2.50
ATT#5 - Design for maintainability and longevity		3.33
Wear and tear indicator or information	Yes	5.00
Possibility of maintenance and repair	Yes	5.00
Accessibility, visibility, reachability and identifiability of key components	Difficult even for a specialist	0.00

Figure 9. Breakdown of the circular product design score for the lithium-ion battery pack

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3.3 Improvements

In this line, following these circularity assessments, the industrial practitioners generated ideas to improve the circularity performance of the electric outboard. In all, more than ten circular economy-related projects have been identified. For confidentiality reasons, they cannot be fully disclosed, but here are some of the insights obtained from the workshop to enhance the circularity potential of the electric outboard:

- Investigate supply chain options for aluminum and thermoplastic components, in terms of reduced transportation and increased recycled content;
- Investigate commercialization strategies that would be accretive and increase circularity, such as:
  - Publishing a disassembly process in multiple formats, e.g., web animations, owner's manual;
  - Leasing electric outboards directly to the professional staff or fish camps;
  - Providing batteries as a service;
- Create an industry consortium focused on setting up infrastructure and communications for circularity – i.e., a collaboration between OEMs, dealers, and other partners;
- Continue to define a transparent take-back process;
- Analyze the trade-offs in designing critical components for Re-X, such as an unlimited fatigue life for the motor bearing wear indicators, as well as modularity in the battery pack for Re-X.

Also, in working through the LCA process, the OEM discussed several internal process opportunities, including: (i) the definition of a process and product lifecycle management (PLM) system refinements to enable, as much as possible, automated LCA calculations at specific stages in a product development program, (ii) the elaboration of a technical process for how to calculate remanufactured products – e.g., BoMs with blended new and reused parts, as well as (iii) additional internal discussions on carbon pricing strategies and decarbonization targets.

To illustrate the potential impact savings that can be induced by these improvement ideas, the previous LCA results (baseline) are compared with the results of new LCAs where the material recycled content is increased for realistic materials, as shown in Figure 10. Note that the absolute impact numbers are not displayed for confidentiality reasons. By increasing the recycled content of metallic parts – i.e., switching from 65% recycled aluminum to 100% recycled aluminum, as well as replacing brass with recycled brass, nickel by recycled nickel, and steel by recycled steel – the carbon footprint allocated to the manufacturing phase decreases by 17%. Similar results (23% of impact reduction allocated to the manufacturing phase) are obtained when increasing the recycled content of plastic parts – i.e., replacing acrylonitrile-butadiene-styrene (ABS) copolymer by recycled ABS, nylon (PA) by upcycled nylon, polycarbonate (PC) by upcycled PC, polyurethane (PUR) by upcycled PUR, and polypropylene (PP) by upcycled PP.

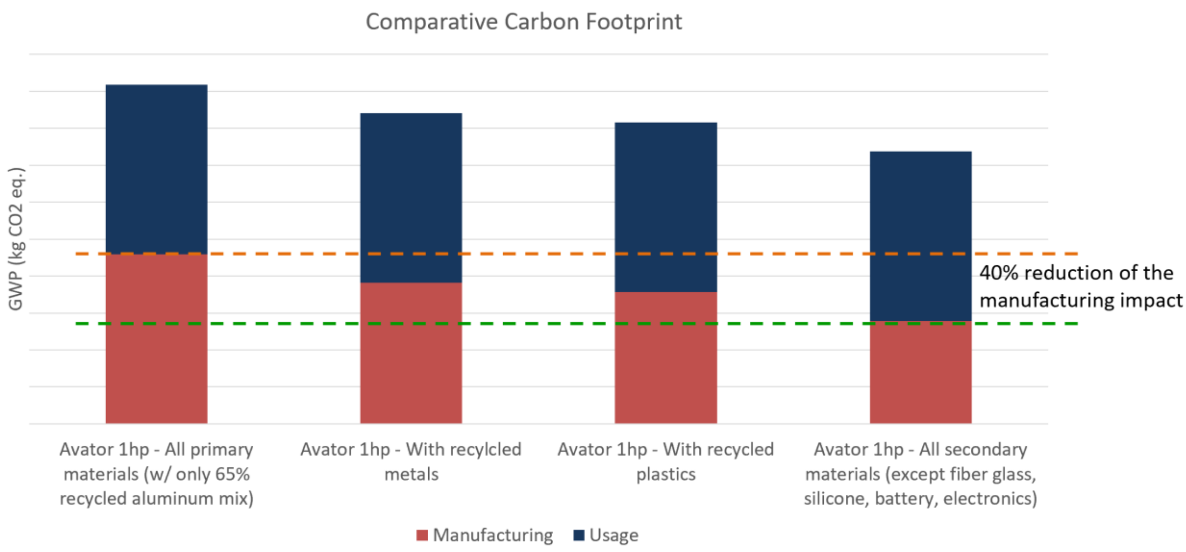

Figure 10. Comparative LCA results, global warming potential indicator

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4 DISCUSSION AND NEXT STEPS

To the industrial participants, these workshops met the following key objectives:

- Learn how to calculate the environmental impact of a design, in alignment with ISO 14040-44;
- Learn how to assess the circularity of a design;
- Complete LCA and Re-X assessments and, leveraging the assessments, generate practical ideas;
- Gather key experts/stakeholders to collaborate on sustainable and circular design, including the Director of Sustainability Engineering Programs, the Remanufacturing General Manager, the Product Technical Lead, Materials Engineers (x2), and Interns (x3).

Notably, the participants found both sessions and their associated Excel-based assessment tools simple to use, efficient, and instrumental for the industrial practitioners: “very easy to use”; “the workshop today was excellent, from my perspective”; “the engagement was very high”; “to bring focus to the Avator Re-X analysis”; “provide an additional way of looking at design, for the benefit of all stakeholders, an additional way to extend the company’s generous product leadership”.

Future works include the quantification of the actual sustainable benefits from closing the loop on electric outboards and, more globally, on recreational boats at different levels. At a material level, after assessing the potential impact savings from bringing a higher percentage of recycled content in manufacturing, the industrial feasibility remains to be validated with material engineers and suppliers. At a product and subassembly level, the next steps will focus on the critical components and parts that can be reused and/or remanufactured, in order to: define selective disassembly steps, define tools and fixtures needed for safe operation, provide field Re-X suitability tests for each selective disassembly level, and estimate the cost of collection, transportation, and disassembly operations. On this basis, realistic scenarios could be generated to compare the environmental impact of different end-of-life and circularity pathways. Importantly, the LCA and CI results can be complemented with leading sustainability indicators (Kravchenko et al., 2020; Saidani et al., 2022) to ensure that an increased circularity leads to positive benefits on the three pillars of sustainable development.

Last but not least, as the industrial participants found both frameworks easy to use and efficient, all the details and resources used to conduct, replicate, or adapt such workshops in various industrial contexts can be made available on demand.

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