COMPARING LIFE CYCLE IMPACT ASSESSMENT, CIRCULARITY AND SUSTAINABILITY INDICATORS FOR SUSTAINABLE DESIGN: RESULTS FROM A HANDS-ON PROJECT WITH 87 ENGINEERING STUDENTS

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ABSTRACT

Considering a growing number of metrics and indicators to assess circular economy, it is of paramount importance to shed light on how they differ from traditional approaches, such as life cycle assessment (LCA) or sustainability performance indicators. This study provides new empirical insights on the correlation between LCA, circularity, and sustainability indicator-based approaches. Specifically, the importance lies in analyzing how the results generated by these different approaches can be used to support the design of products that are not only circular, but also sustainable. A practice-based project involving 87 engineering students (divided into 20 groups) is conducted with the aim to compare and improve the circularity and sustainability performance of three product alternatives of lawn mowers (gasoline, electric, autonomous). To do so, the following resources are deployed: 18 midpoints environmental indicators calculated by LCA, eight product circularity indicators, and numerous leading sustainability indicators. Critical analyses on the usability, time efficiency, scientific soundness, and robustness of each approach are drawn, combining quantitative results generated by each group with the feedback of future engineers.

Keywords: Circular economy, Sustainability, Ecodesign, Indicators, Case study

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1 INTRODUCTION

1.1 Context and motivations

With a circular economy (CE) rapidly getting its momentum as a way of boosting business opportunities and potentially bringing significant environmental benefits, tools and approaches to support the development, evaluation, and implementation of CE initiatives are of the utmost importance. Currently, most products and associated services are not systematically designed to be integrated into a circular economy model (De Wit et al., 2020). Product-level circularity indicators (C-indicators) can provide a practical approach to support the (re-)design of products adapted for a CE. Saidani et al. (2020) provided examples of how C-indicators can support designing circular products by defining CE requirements and comparing the circularity potential of design alternatives. Yet, further experimentations of C-indicators with practitioners (designers, engineers, or managers) are needed to increase their actual uptake in industry. On the one hand, moving towards CE practices is increasingly acknowledged to contribute to sustainable development goals (Schroeder et al., 2019). On the other hand, circular economy and sustainable development are not systematically synonyms, and some trade-offs might occur between more circularity and other environmental, economic or social – a.k.a. the triple bottle line (TBL) – indicators. Replacing virgin material sources with recycled materials offers a great opportunity within CE, however, the issues of resource intensity of the recycling processes and the quality of a recycled material (Allwood, 2014) might lead to an increase in the overall environmental impact. In this line, the correlation between circularity scores and sustainability performance needs to be further investigated. To Korhonen et al. (2018), scientific research is needed to secure that the actual environmental impacts of CE work toward sustainability. Thus, it is key to support early understanding when circular strategies contribute to sustainability, by investigating approaches to compare product designs, identify improvement opportunities, and provide a basis for decision-making.

A variety of C-indicators has been proposed to measure CE performance (Parchomenko et al., 2019; Saidani et al., 2019; Roos Lindgreen et al., 2020); however, it is questionable to what extent the C-indicators can be used as proxies for environmental and economic performance. According to Kravchenko et al. (2020a), CE measurements should be completed by sustainability measurements from a holistic TBL perspective. However, combining CE and TBL measurements can be seen as both an opportunity and a challenge for industrial companies, which leads to uncertainties on how to incorporate measurement results during the design and development stages as well as how to objectively report the benefits of their CE initiative by linking them to sustainability performance measures. Additionally, while there is a wealth of methods and tools (such as life cycle assessment (LCA), C-indicators and corresponding assessment frameworks, or stand-alone leading sustainability indicators) to evaluate the performance of a product from a sustainable and circular perspective, the complementary between these approaches remains unclear. Therefore, more research is needed to validate the correlations between the sustainability performance of products and results from product-level circularity indicators, which might help to increase their uptake by industrial practitioners when designing products for improved circular and sustainable performance. As a result, this study aims at investigating and shedding new lights on such correlations to provide novel empirical insights on that matter.

1.2 Research approach and objectives

The main research question that is driving this study is: to what extent – how, which, when, and where in the design and development process of products – circularity and sustainability indicators could be combined to come up with more circular and sustainable solutions? To answer this multifaceted question, a collaboration between a team of researchers at CentraleSupélec (CS), Université Paris-Saclay, and a research group at the Technical University of Denmark (DTU) is established, bringing their complementary expertise in circularity and sustainability indicators, respectively. CS has developed a classification and an online selection tool (http://circulareconomyindicators.com/) for circularity indicators. DTU has developed a database and an Excel-based selection tool for leading sustainability indicators. The overarching goal of the present research collaboration is to ensure that the implementation of CE strategies contributes to sustainability. In the present paper, based on a hands-on project with 87 master students in industrial engineering, new empirical insights are brought to the following sub-questions: Are circularity scores consistent and well-aligned with sustainability scores when assessing the performance of a product? How can LCA, C-indicators, and S-indicators

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complement each other to develop more circular and sustainable products? What is the practical utility (e.g., user-friendliness, reliability) of such approaches to future engineers? In the project, the students, as future engineers, had to apply and compare LCA, C-indicators, and S-indicators to assess and improve the performance of three product alternatives. Particularly, the strengths and weaknesses, possible synergies and trade-offs between life cycle-, circularity, and leading sustainability indicator-based approaches are discussed. Practical insights on how to combine existing approaches are given and justified based on the outcomes generated throughout this project, including quantitative results comparing these indicator-based approaches and qualitative feedback from future engineers.

2 MATERIALS AND METHODS

2.1 Literature survey: assessing the circularity and sustainability performance of products, and associated trade-offs

According to Geissdoerfer et al. (2017), the TBL is the system prioritized for sustainability, while the economic system is prioritized in a CE with the goal of eliminating all resource input into and leakage out of the system. Three main relationship types between the circular economy and sustainability are depicted and illustrated by Geissdoerfer et al. (2017): (i) conditional relation (i.e., one of the conditions for a sustainable system could be necessary but not sufficient, i.e., sine-qua-non); (ii) beneficial relation (i.e., more circularity induces more sustainability); and (iii) trade-off relation (i.e., a circular economy strategy having costs and benefits in regard to sustainability). Yet, in practice, decision making for product circularity and sustainability could be a challenging task, where complex trade-offs might occur, such as a design decision between the minimization of energy use or the reduction of waste generation. More sustainability-related trade-off types, situations, and occurrences are described in Kravchenko et al. (2020b). The trade-offs between sustainability and circularity aspects, when not considered and analyzed in a structured manner, may lead to uninformed decision-making and undesired outcomes.

2.1.1 Life cycle assessment indicators

Life cycle assessment (LCA) is an internationally standardized methodology (ISO 14040-14044, 2006) used for the quantitative environmental impact assessment of products, processes, services, and systems, throughout their life cycles, from materials acquisition to processing, transportation, usage, and end-of-life. LCA can be particularly useful in comparing alternate strategies, understanding the environmental trade-offs between benefits and impacts of different systems, and thereby make informed decisions (Kloepffer, 2008; Laurin et al., 2016). According to ISO standards 14040 (2006) and 14044 (2006), the purpose of the life cycle impact assessment (LCIA) phase is to establish a linkage between the life cycle inventory (LCI) of the system under study and its potential environmental impacts and damages. Particularity, characterization methods (eco-indicators) measure the impact and damage caused by human-made actions and products on environmental categories. The ReCiPe 2016 Midpoint (H) indicators are the ones used in the present project. The ReCiPe Midpoint indicators notably quantify the environmental impacts in 18 categories, including, for example, global warming potential (kg CO2 eq.), stratospheric ozone depletion (kg CFC11 eq.), terrestrial acidification (kg SO2 eq.), freshwater ecotoxicity (kg 1,4-DCB), human carcinogenic toxicity (kg 1,4-DCB). A detailed description of the ReCiPe LCIA methodology can be found in Huijbregts et al. (2017).

While LCA is a sound and relevant approach as aforementioned, its actual applicability in the context of the ex-ante assessment of CE strategies and as a support for early decision-making is often limited (Kravchenko et al., 2019). Further roadblocks of the use of LCA in industry have been highlighted in the literature (Cerdas et al., 2017): (i) performing an LCA is complex, and communicating the results also require a certain level of expertise, or support from environmental experts; (ii) collecting and compiling data (through LCI) can be time-consuming and costly; and (iii) LCA does not allow to identify hotspots quickly and to decide between environmental trade-offs in a straightforward way. The aim of this project is also to get the feedback of future engineers on the applicability and practicability of LCA – to challenge and discuss these statements – in comparison with circularity and leading sustainability indicator-based approach to assess and develop more sustainable products.

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2.1.2 Leading sustainability indicators

Sustainability indicators have been comprehensively reviewed by scholars. Their classification is widely acknowledged and often associated with the TBL dimensions (economic, environmental, social) (Finkbeiner et al., 2010). Sustainability indicators could support sustainability assessment in the early stages of any business process (for instance, at the conceptual design stage during product development) to provide visibility about the potential sustainability implications of the proposed solutions (Shahbazi et al., 2020). Specifically, leading performance indicators have the ability to produce simpler measures of environmental (and other TBL) performance that can be effective for driving actions for improving the environmental performance of products (Kravchenko et al., 2019). Leading performance indicators for sustainability, or S-indicators, appear thus as a promising and commendable approach to assess the sustainability performance of CE initiatives: "For a meaningful ex-ante sustainability assessment, leading indicators are preferred over lagging, as they can be used to plan and monitor the effectiveness of proposed actions by focusing on critical areas or resolving any uncertainty early in the planning and development process" (Kravchenko et al., 2019). Leading indicators are considered as simple "input/output" indicators (e.g., material cost per unit of product, take-back offerings for products), and thus offer better measurability and control over impact in the early design stages. On the other hand, lagging indicators are considered as "outcome/impact" indicators (e.g., global warming potential, customer retention), provide results about past performance and are often challenging to be interpreted by practitioners into improvement actions, despite having a higher certainty of data (e.g., LCA results).

2.1.3 Circularity indicators

C-indicators can be defined as measuring instruments to quantify the performance and progress of systems in a CE perspective (Saidani et al., 2020). The number of circularity indicators, C-indicators, has considerably increased in the past few years, leading to both utility and confusion in regards to their purpose and application. More details on the classification of CE indicators can be found in the taxonomy of 55 C-indicators proposed by Saidani et al. (2019), and in the multiple correspondence analysis of 63 CE metrics by Parchomenko et al. (2019). More recently, based on a systematic literature review, Roos Lindgreen et al. (2020) performed a critical analysis on 74 approaches, methods, and tools to assess CE at the micro-level. On this basis, they advocated for a closer collaboration between researchers and practitioners to consider end-user needs in the design of CE assessment approaches. Additionally, through a previous workshop experimenting four C-indicators on an industrial product (Saidani et al., 2020), empirical evidence has been brought on how product C-indicators can be suitable to help designing more circular products. The Material Circularity Indicator (MCI), Circular Economy Indicator Prototype (CEIP), Circularity Potential Indicator (CPI), and Circular Economy Toolkit (CET) have been positioned among the pool of design methods to assist the design and development process of products. It has been shown that they can quickly guide practitioners towards areas of improvement and most promising circular strategies. These C-indicators take previous qualitative design guidelines to the next level, such as the VDI guideline 2243 "Designing recyclable technical products" (2002) that provides engineers with hints on suitable designs for product recyclability (including, use recyclable and reusable materials, employ modular design for easy accessibility and non-destructive disassembly), to make sound and quantitative circular decisions during the early phase of product development.

2.2 Project description, workflow and resources

2.2.1 Project context and positioning

The project is part of a newly developed engineering challenge term "Circular Economy and Industrial Systems" at CentraleSupélec, Université Paris-Saclay, for which 87 Master's students in engineering enrolled from February to April 2020. During this 8-week sequence, the students live 9 teaching hours of introductory modules (conferences, workshops, visit), 34.5 teaching hours of courses in Circular Economy, and 80 learning hours on a project with an industrial partner. The first half of the course (sessions 1-6, 3 teaching hours each) covers the different dimensions of CE to provide to the students a global vision of the field, including lecture and workshop on: product end-of-life, ecodesign, extension of product lifespan, responsible consumption, sustainable procurement, functional economy and responsible consumption, industrial and territorial ecology. The second half of the course (sessions 7-11) is focused on the deployment of CE tools. This includes Material Flow Analysis (MFA), to map

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material and energy flows, LCA, to calculate potential environmental impacts, as well as circularity and sustainability assessment framework to drive CE projects. These tools are applied directly to one pedagogical project (different from the industrial project with a real client) described in section 2.2.2, and this project counts for 70% of the students' final mark for the course. Figure 1 illustrates this pedagogical program and highlights the sessions used for the experiment.

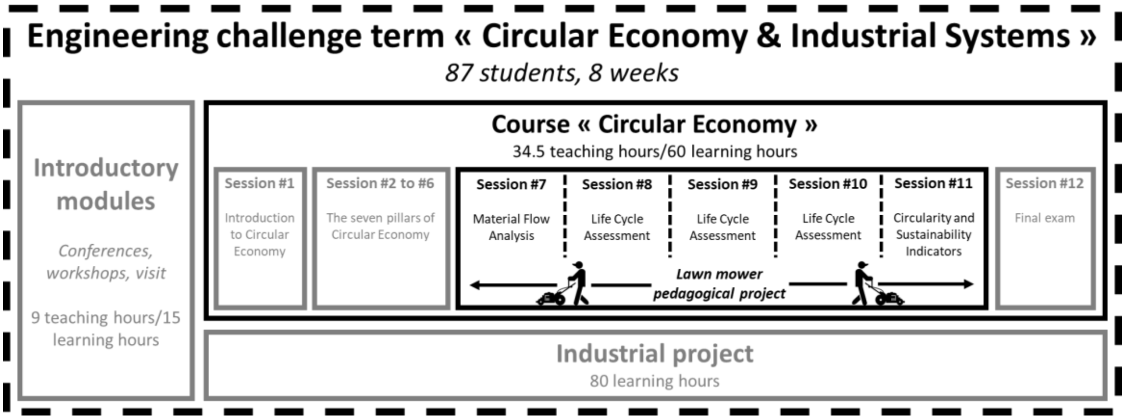

Figure 1. Configuration of the pedagogical program used for the experiment

2.2.2 Project narrative and resources

This pedagogical project aims to evaluate, compare, and enhance the circularity and sustainability performance of three lawn-mowing solutions from a life cycle perspective. The challenge was introduced to the students in the following way: "You just got a new house with a beautiful ¼ acre yard (1000 m2). To take care of your garden, you are considering buying a mower to properly trim and edge your lawn. As an environmentally conscious citizen, you wonder what solution is eco-friendlier. Considering the size of your yard, three lawn-mowing solutions appear as potential candidates: (1) a conventional gasoline push mower (product A), (2) an electric-powered push mower (product B), (3) an autonomous mower (product C). The questions you set out to answer are: What is the environmental impact of each solution? Which sustainability indicators are relevant to set up a sound comparison? How well these products (components, materials) performed in a circular economy? As an engineer, what would you do to improve their circularity and sustainable performances?" Generic lawn mower models were used for the three solutions to be analyzed, and the same 4-page datasheet was provided to each of the 20 groups of 4 students each. This datasheet contained three main sections with information related to (i) the design and manufacturing, (ii) the usage and maintenance, and (iii) the collection and end-of-life of the three product alternatives. This datasheet is available on-demand. The 87 students were split up into 20 groups of 4 to 5 students, each group working independently.

2.2.3 Life cycle impact assessment part

Students were trained on how to perform a life cycle assessment (LCA), following the four steps described in the ISO standard 14040 (2006). They use the free LCA software OpenLCA 1.10.3, the database ecoinvent 3.2, and the ReCiPe 2016 Midpoint (H) LCIA methodology. For the impact assessment phase, they have been asked to: (i) evaluate the environmental impact of each solution, (ii) compare the environmental impact of the three solutions, and (iii) propose relevant charts to display the results. For the interpretation phase, they have been asked to: (a) identify and describe the environmental hotspots for each product, and (b) explain if they are able to decide which lawn mowing solution is better from an environmental standpoint. In terms of implication and critical analysis, the guiding questions were as follows: What are your suggestions to decrease the environmental impact of the lawn mowing industry? What are the limits of your study? Can you assess the robustness of your study (by making a sensitivity analysis, for example)?

2.2.4 Circularity assessment part and proposition of eco-improvement

After the life cycle impact assessment and results interpretation of the three products, each group experienced two of the eight C-indicators selected for this study, namely: (i) MCI, (ii) CEIP, (iii) CPI, (iv) CET, (v) Circularity Calculator (CC), (vi) Circular Economy Index (CEI), (vii) Circularity (CIRC), and Longevity (LONG) indicators. More information for each of these C-indicators can be

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found in the database linked to the taxonomy of CE indicators, now available online (http://circulareconomyindicators.com/). The focus is thus put on product circularity indicators (Parchomenko et al., 2019), i.e., at the micro-scale of CE implementation (Saidani et al., 2017; Shahbazi et al., 2020) to evaluate, compare, and augment the circularity of the three product alternatives used for the students' project. Each of the 20 groups was asked to use two predefined C-Indicators, and to ensure a good balance between groups, each group used one computer-based tool, and one formula-based indicator to compute the C-indicators. A pre-filled one-page response document was provided for each C-indicator, including all the necessary resources (e.g., Excel spreadsheet, website, or formula) to compute the C-indicator in question. Regarding the assessment phase, the students have been asked to report the results (circularity scores) as well as to justify any assumptions made, when needed. Then, based on the results of the circularity assessment, they have been asked to propose at least four solutions (e.g., in terms of design, business model, incentives, etc.) to augment the circularity score of lawnmowers and their eco-system. By increasing the circularity performance of this product, they have been asked to comment on what are the expected benefits (or impact transfers) in terms of environmental and economic sustainability.

2.2.5 Sustainability performance assessment part and critical analysis

For the evaluation of the sustainability performance of the three lawn-mowing systems, each group of students has been asked to select and apply up to eight indicators from the database of leading S-indicators (Kravchenko et al., 2019) that make sense according to the improvement areas or solutions proposed by them in the previous part. They also had to explain their thought process in the selection and calculation of these indicators (e.g., if some additional details were needed, or if some assumptions were made). In all, in the end, each group had three different assessments of circularity and sustainability: LCA results (lagging environmental impact indicators), C-indicators (two different indicators per group), and leading S-indicators (up to eight indicators per group). On this basis, they have been asked to reflect on these diverse evaluation approaches, e.g., if they are consistent to one another, complementary, or contradictory, as well as to elaborate on the insights they provide (e.g., for decision-making), and their user-friendliness (e.g., level of expertise required, time needed, data required, user interface). Finally, in the response document, room was left for open comments, guided by the following question: How or to what extent the indicators provide insights to improve the sustainability performance. Shall one absolutely increase the circularity score to be more sustainable?

3 RESULTS AND INTERPRETATIONS

In this section, the quantitative results – i.e., the LCA-, circularity-, and sustainability-based indicators – generated by each group are analyzed, compared, and interpreted in the light of assessing and improving the sustainable performance of products in a CE perspective. To do so, first, LCA and C-indicators results presented in corresponding graphs, are reviewed on an individual basis. Then, following the workflow of this project, the correlation between environmental impact indicators and C-indicators is illustrated and discussed. Next, the inputs and results provided by leading S-indicators to evaluate the relevance of the proposed improvements are commented. Finally, further qualitative findings from this project are discussed, including the feedback and critical analysis from future engineers on these different approaches.

3.1 Stand-alone LCA results and environmental trade-offs

Different groups went for different ways to represent and communicate the LCA results, including bar charts, radar diagrams, or tables, as illustrated in Figure 2. Due to environmental trade-offs among the 18 ReCiPe midpoints, it was not straightforward for the engineering students to simply identify or recommend one single solution (i.e., the most commendable from an environmental standpoint). In fact, in the spider diagram of Figure 2 (right side), the mowing solution A has the least global warming potential but the highest agricultural land occupation impact. For instance, group #11 mentioned: “we cannot immediately say which mower is the best. Indeed, depending on the criteria that we favor, the A, B or C can stand out”. As such, to provide a sound and well-justified recommendation on which mower to select based on LCA results, most groups tried to consider the most relevant LCA-based indicators for this specific context of mowing a yard, such as global warming, human toxicity, or land use occupation. The selection of these indicators (to draw realistic recommendations for decision-making) could also be based on the sustainability strategy of the manufacturer.

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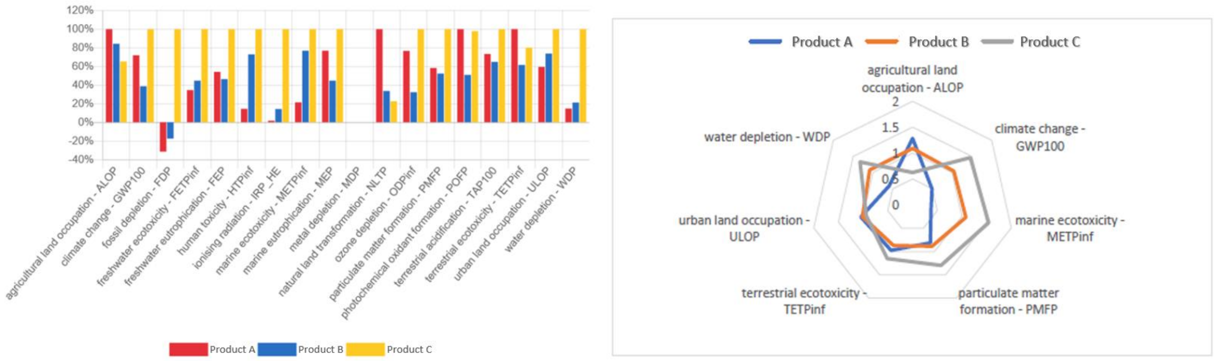

Figure 2. Illustration of LCA results for different groups

Additionally, according to the students' feedback, it was not straightforward to propose concrete design improvements based on the LCA results, nor to assess the impact of a change in design in a practical way. For example, group #10 commented that while "LCA and MFA are two ways of evaluating the impact of a CE strategy of a product, they also have their limits. They are based on products already produced and allow a good assessment of past performance, but make it more difficult for engineers to make decisions about products that are still to be designed." They added: "we are therefore interested in new circularity indicators, which allow us to add a more systemic view to our study. " Finally, one group (#15) brought out the geographic dependence of LCA results, notably for the use phase impact: "this impact could have been distributed differently if another country had been chosen to use the mower."

3.2 Stand-alone C-indicators and robustness of the assessment

Each of the 20 engineering student groups experienced two C-indicators according to the distribution mentioned in sub-section 2.2.4., so each C-indicator has been computed five times (i.e., by five different groups), having the same initial data sets for the three products. The variability and robustness of these C-indicators are illustrated through the box and whisker plot in Figure 3. While the MCI, CPI, CEIP, CC, and CEI deliver an overall score between 0 and 1 (or a circularity percentage), the CIRC and LONG scores have been normalized using the min-max feature scaling, for comparison purposes. Also, the CET, being a qualitative indicator, is not represented in this graph but discussed in the critical analysis hereafter. Note that a detailed description of these C-indicators is available in Saidani et al. (2019).

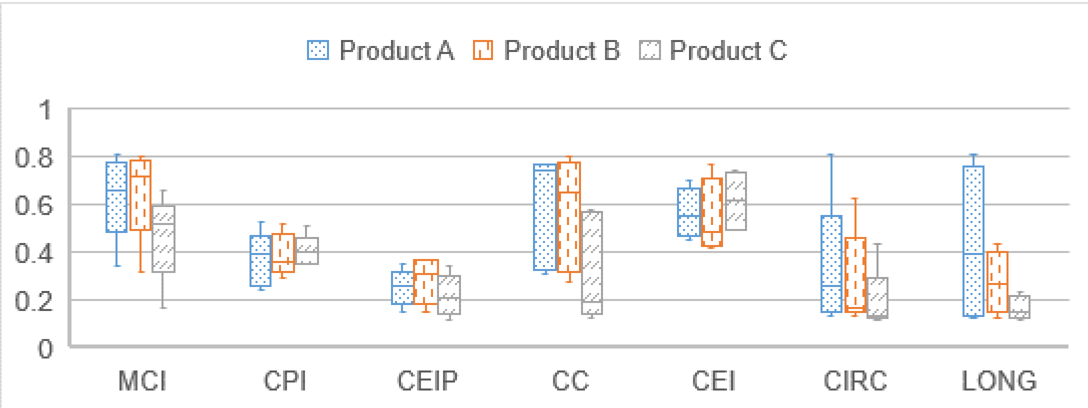

Figure 3. Box plot of the circularity scores (each C-indicator was computed by five groups)

On one side, the results from the CPI and CEIP are consistent with one another: they both assess a circularity potential of design proposals, tend to underestimate the circularity performance (compared to the other C-indicators here) due to many questions (conditions) to reach a high, or even medium, circularity score, and present of low variability between groups. On the other side, the MCI and CC, both material flow-based indicators assessing an effective circularity, present similar trends by being highly sensitive to the assumptions set by each group (i.e., in the present case, on actual end-of-life fate of the products, and their associated components and materials). The CIRC and LONG, assessing as well an effective and intrinsic circularity of resources, present a distinctive variability between groups. Finally, the CEI appears to be a stand-alone and complementary indicator here by assessing the economic value of material recirculation through CE loops.

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3.3 Correlation between LCA and C-indicators

The color-coding in Table 1 shows the level of correlation from the agreement (green) to disagreement (orange/red) between the LCA and circularity indicator-based approaches according to the product alternative recommended (higher circularity for the C-indicators, lower environmental impact for the LCA-based indicators). Overall, the LCA and C-indicators seem to yield concordant results, as noted, for example, by group #3. Particularly, for most groups, the MCI and CC, both material flow-based indicators, are in line with the LCA results. The same remark applies to the CET, CIRC, and CPI indicators. On the other hand, in the present case, the CEI, assessing the economic value of material recirculation, recommends another product solution than the one favoured by LCA results. Note that the variability of the solutions recommended by each group can be explained both by the LCA indicators selected for decision-making (as further explained in sub-section 3.1), as well as by the assumptions made to compute some C-indicators.

3.4 Complementary leading S-indicators and trade-offs management

According to the eco-improvement solutions proposed by each group, different leading sustainability-related performance indicators were selected from the database of 290+ S-indicators, composed of 70 economic (EC), 175 environmental (ENV), and 51 social (SOC) indicators. At this point, the students were less guided, and more assumptions had to be made to compute the S-indicators, which makes the comparison between groups difficult. However, it remains interesting to analyze the differences or similarities between future engineers in the choice of S-indicators, as well as how they took potential trade-offs into account, i.e., their thinking process to recommend one particular product alternative or solution. As shared by several groups, two different sets of indicators could lead to different recommendations. On this basis, group #4 mentioned they “can see the advantage of combining two approaches to make a decision that is most respectful of the principles of circular economy and sustainable development”. In all, among the 20 groups, 52 different S-indicators were selected (19 EC, 27 ENV, and 6 SOC), with the two specific EC indicators being picked up by three different groups (e.g., the EC4 “Revenues from reused/repurposed products), and five ENV indicators being used twice (e.g., the ENV73 “Fraction of recyclable materials”). For instance, the EC4 has been appreciated by several groups in the present context as it could encourage the manufacturer to develop a new recovery strategy for old lawn-mowing systems.

Table 1. Correlation between LCA and C-indicators (A, B, C relate to the three products)

#	Ranking per group (> means "performs better than")			C-indicators experimented* and interpretation (correlation) *MCI: Material Circularity Indicator; CC: Circularity Calculator; CPI: Circularity Potential Indicator; CEI: Circular Economy Index; CET: Circular Economy Toolkit; CIRC: Circularity; CEIP: Circular Economy Indicator Prototype; LONG: Longevity
	LCA indicators	C-indicator 1	C-indicator 2	
G1	A > B > C	A > = B > C	A > = B > C	MCI and CC, material flow-based indicators, quite consistent
G2	A > = B > C	A > B = C	C > A = B	CPI, CEI
G3	A > = B > C	A > = B > C	A > B > C	CET and CIRC, well-aligned with each other and LCA results
G4	A > C > = B	B > = C > A	A > B > C	CEIP and LONG, no conclusive interpretation
G5	A > B = C	A > = B > C	B > = A > C	MCI and CC
G6	B > A = C	B > A = C	C > A = B	CPI, CEI (indicating the economic value of material (re)circulation)
G7	B > A > C	B > = A > C	B > = A > C	CET and CIRC
G8	B > C > A	B > = A > C		CEIP
G9	B > = A > = C	A > = B > C	A > = B > C	MCI and CC
G10	A > C > = B	C > B > = A	B > C > A	CPI, CEI (electric mowers having a higher residual economic value)
G11	A > B = C	A > = B > C	A = B > C	CET and CIRC
G12	B > C > A	A = B > C	A > B > C	CEIP and LONG
G13	B > A > = C	B > C > = A	B > = A > C	MCI and CC
G14	C > B > = A	C > = B > A		CPI well-aligned with LCA results
G15	C > B > A	A > = B = C	A > B > C	CET and CIRC
G16	A > = B > C	A = B > = C	B > A > C	CEIP and LONG
G17	B > A > = C	A = B > C	A > = B > C	MCI and CC
G18	A > = B > C	A > = B > = C	B > = A > C	CPI, CEI
G19	B > C > A	A = B = C		CET
G20	B > A > C	B > = A > C	B > A > C	CEIP and LONG

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4 DISCUSSION AND PERSPECTIVES

Here, the feedback of future engineers on the LCA, circularity, and sustainability indicator-based approaches is discussed, following the guiding questions listed in sub-section 2.2.5 (e.g., on the contribution of these indicators to the decision-making process), to provide practical recommendations on: which indicator-based approaches to use (e.g., LCA, C-indicators, leading S-indicators, or a combination), when (e.g., positioning in the engineering design process), for who (e.g., designers, engineers, managers, LCA experts), and how to combine these sets of indicators to come up with augmented insights to support decision-making?

Reflecting on the differences between both leading and lagging indicators for sustainability measurements and CE indicators, one group (#6) stated: “as future engineers, it is crucial for us to understand this complexity by mastering a wide variety of indicators and being able to arbitrate between them to help decision-makers (who are not always trained in very technical indicators like LCA) to make the right choices about circularity and ensuring that the circular solutions they choose are well anchored in sustainability. We think that it is particularly important to master both lagging indicators, to account for the existing and its present impact to correct it if necessary, and leading indicators, to evolve the models.” To another group (#1), “the risk of not taking into account the two types of indicators would be to arrive at a solution that is ultimately counterproductive”. Accordingly, group #9 commented that “these three types of indicators seem to be completely complementary” explaining that “LCA results allow analysis of past performance in order to draw conclusions about decisions to be made in the future”; “C-indicators make possible to have more numerical values and therefore to make estimates of future developments”; and, “S-indicators further tell us what to do (influence future choices at a company level)”. Similarly, group #13 mentioned that “life cycle assessment in OpenLCA allowed us to evaluate the current impact for all three products, while circularity and sustainability indicators were more useful for identifying potential modifications in the products that would make them eco-friendlier. They could be easily understandable from graphs and could be advertised to the general public, and they provide insights on what are the main issues with these product designs.” Similarly, group #18 stated that “C-indicators make it possible to identify points for improving the circularity of products. However, adding the S-indicators to them is necessary to judge the effectiveness of a measure.”

Other groups were more nuanced. For instance, group #2 concluded that “the three approaches used (LCA, C-indicators, S-indicators) do not answer exactly the same questions, so it is difficult to speak of consistency between these indicators”, while mentioning “a real complementarity between these two approaches: LCA allows an ‘absolute’ quantitative analysis of the impact of the product, while the leading indicators allow them to assess their performance in a more qualitative and ‘relative’ manner, taking into account other aspects, sometimes more related to socio-economic issues.” In addition, reflecting on their experience with these three different indicator-based approaches, group #11 found that “C-indicators are more useful for engineers and designers, leading S-indicators are more used by decision-makers who have to manage dozens of products in a company.” In this regard, group #15 added that the “S-indicators appear to be the simplest to use, since they require only a few reasonable hypotheses to be implemented.” Eventually, regarding the usability of each approach, most groups agreed that product level C-indicators associated to a computer-based tool, and leading S-indicators, are the quickest and friendliest to deploy, while LCA indicators “require a mastery of the software”.

Moving forward, there seems to be a significant value opportunity to combine such approaches to overcome the current strengths and limitations of existing LCA, circularity, and sustainability indicators. The new empirical insights generated results that can be supplemented with additional case studies to give recommendations on the deployment of the most appropriate approach(es) based on a given context and/or specific need(s). For instance, the analysis of disruptive alternative solutions for mowing could bring new trade-offs to the discussion table. In fact, the three mowing solutions considered here are mechanical engineering and electronic products, which makes their sustainability potential reduced in regard to more ecological alternatives that could bring similar functional services. In future work, one can imagine a guiding flowchart to help a user (whether a designer, engineer, or manager) to navigate between these indicators, as well as to aggregate existing and relevant approaches into an ad hoc integrated solution. Additionally, it would be beneficial to compare approaches that focus on social performance and impacts, so as to provide a holistic TBL consideration of sustainability and discuss potential trade-offs between and within economic, environmental, and social dimensions and circularity performance. Last but not least, we do believe

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that similar practice-based projects could be replicated in various curricula to train not only engineers, but also designers, managers, and industrialists of tomorrow in mastering and deploying the right methods, tools, and indicators to design sustainable products and take appropriate and sound decisions in favor of a more circular and sustainable economy (Faludi et al., 2020). As such, all the materials and resources (including the dataset, the pre-filled responses documents, as well as the computer-based tools to select and compute the indicators) are available on-demand, to be reused and disseminated.

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