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Parametric LCA integrating a product's State of Health: A decision-making tool based on environmental impact in the context of circular strategy.

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Abstract

Circular processes such as remanufacturing, reuse, recycling, make it possible to extend the life of products and thus reduce their environmental impact. However, they introduce uncertainties of quantities and qualities that bring significant challenges for manufacturers and others stakeholders. To reduce such uncertainties and give decision-makers more information for selecting a circular strategy driven by the environment, a parametric life cycle analysis method is essential. The aim of this article is to propose a method based on the performance parameters of each process of product closed-loop to calculate the environmental impact of a product in different closed loops, considering the product's state of health. To achieve this objective, the product life cycle process with closed circular processes were first specified. Then, its parameterization was completed to simulate different scenarios. Based on parameters defined, formulas to facilitate the simulation of several circular scenarios for a given product has been defined. This allows identifying the circular strategies with the lowest environmental footprint. Illustrated by a case study on an electric circuit breaker, our approach demonstrates its effectiveness in supporting eco-responsible decisions.

Keywords: Parametric LCA; Circular Strategies; Decision-making; Decision-Aid; State of Health

1. Introduction

Today, the environment is one of the greatest challenges. Industry has always been operating on the basis of a linear economy, i.e., it designs a product, extracts the raw materials, and transforms them to produce a final product. The final product is then integrated in another product, or directly used by the end-customer, who ultimately disposes it as waste. In this context, the main objective has always been to increase profits either by increasing productivity or product quality or responding to changing customer needs. With this linear economy strategy, industry is one of the biggest contributors to environmental degradation [1]. Today, in the context of sustainable development, they are transforming their economy together with scientists to make it more circular. The aim is still to increase profits, but with environmentally-friendly activities that reduce the environmental impact (EI) they generate. The circular economy (CE) aims to extend the life of products and thus reduce their impact on the environment, which introduces more uncertainties on quantity and quality of recovered products into the circular value chain [2]. These uncertainties pose even greater challenges to manufacturers than before. In addition, there are many circular processes such as remanufacturing, refurbishing, reusing, repurposing, repairing, recycling, etc. Furthermore, industry sometimes has a wider range of products. All these issues make it difficult to define a circular strategy (CS). It is therefore ambiguous for industrials to decide which CS to implement in this context. There is a real need to support them in defining a CS suited to their activities and which is environmentally viable. To meet this need, a methodology is required for simulating different CS products in different use cases, taking into account the issues mentioned above. This article proposes a method for assessing the EI of a product based on the Life Cycle Analysis (LCA) at each stage

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of the product life cycle [3]. This method integrates the State of Health (SoH) of the product into the simulation, as well as the performance parameters of each circular process.

The remainder of this article is organized as follows: Section 2 summarizes the state of the art and formulates the gaps in the form of a research question. The proposed methodology is presented in Section 3. The parametric LCA method is developed in Section 4. Section 5 presents an application of the proposed method to an electric circuit breaker. Section 6 is dedicated to analysis and discussion. Section 7 concludes.

Nomenclature

LCA	Life Cycle Analysis
SoH	State of Health
CE	Circular Economy
CS	Circular Strategy
Sc	Scenario
EI	Environmental Impact
EoL	End-of-Life
EoU	End-of-Use
EIME	Environmental Improvement Made Easy

2. State of the art

Making the decision to select a CS with the lowest EI is a real challenge. Many researchers have conducted comparison study to support the decision making. It is the case of Sutherland et al [4] who carried out a comparative analysis of the EI of remanufacturing and the EI of manufacturing of a diesel engine. Their aim was to highlight the benefits of remanufacturing to help manufacturers make decisions about the circularity of their products. One of the limits of CS is uncertainty, which poses significant challenges for industrials.

Some researchers have also addressed those limits. Harter et al. [5] presented a method to carry out the Life cycle Energy Assessment with the goal to reduce the uncertainties influence at the design stage. Moreover, decision on the environmental-based choice of the optimal CS should be done early at the design stage [6]. Numerous papers evaluated the EI of products both in linear [7] and circular [8–12] context according to the recommendations of standardized LCA methodology.

In that way, Gehin et al. [3] proposed an LCA method for assessing the EI of a product at each stage of its life cycle. This method is very useful for simulating the EI of an EoL scenario to support decision making in CE at the design stage. It is based on the calculation of the EI per stage of product life-cycle, such as the raw materials stage, the component manufacturing stage, etc. Those papers perform LCA on the closed-loop process without addressing the simulation of scenario with parameters.

This is one of the challenges taken up by Luis Amaya Rivas in his thesis [13]. He proposed a methodology to simulate remanufacturing and recycling closed-loop scenario using parameters at each stage of the product Life cycle. This parameterization poses an allocation problem at certain stages of the process, depending on the boundary chosen for the study [14]. Luis Amaya Rivas proposed a parametric method for simulating circular scenarios for a product use case. But he did not address simulation for different use cases and for multiple use of the product and its components in a sales business model. Furthermore, he does not consider the SoH of the used product that is one crucial to define a CS [15]. The main challenge that this paper tackles is how can manufacturers be helped to easily make a decision on the choice of environmentally optimal CS, considering different use cases of the product and its SoH? The following sections attempt to give an answer to this question.

3. Methodology

The aim of this article is to establish a methodology that allows simulating the EI of the circular life of a product based on its SoH and the performance parameters of each stage of the closed-loop processes. This aids decision making on selecting the optimal circular process for different use cases. This methodology is made up of four main parts. For the first part, the closed-loop processes are modelled from raw material extraction to the End-of-Life (EoL) phase. The closed-loop processes are Remanufacturing, Reuse and Recycling. Parameters, some of them considering SoH, are defined for each stage of the processes, with the aim of simulating different alternatives. In the second part, based on the closed-loop processes and parameters previously defined, formulas for assessing the EI of the product by unit of use and at each stage of the product life cycle are determined. In the third part, three scenarios and different use cases were defined in order to compare circular strategies, and identify the one with the lowest EI value. Finally, calculations are performed to determine the EI of each stage of the closed-loop process. These calculations have been refined and validated using LCA software SimaPro and EIME in the fourth step.

4. Parametric LCA method

The parametric LCA method is a method that uses parameters at each step of the product life cycle to simulate EI of CS scenario. This method is inspired by the thesis of Luis Amaya Rivas [13] and the work of Gehin et al. [3]. The objective is to help manufacturers to select the lowest EI circular strategy for their business by testing different alternatives. This method is made up of three main parts. The first part, which is the definition of the closed-loop process and the parametrization, is presented in the next sub-section.

4.1. Closed-loop process and parametrization

The parametric LCA is defined to simulate three CS, namely the remanufacturing, reuse and recycling of product components. The aim is to keep the product and its components in a life cycle as long as possible. The closed-loop process has been defined at both single component and product assembly level. Two types of recovery level have been integrated. One is the recovery of a product at End-of-Use (EoU), i.e., a product recovered before its EoL and still able to fulfil its main function. The other is the recovery of a product at EoL, i.e., a product recovered for disposal because it can no longer fulfill its main function. The EoU strategies on product-level considered here are reuse, remanufacturing and recycling of components. The EoL strategies considered are recycling,

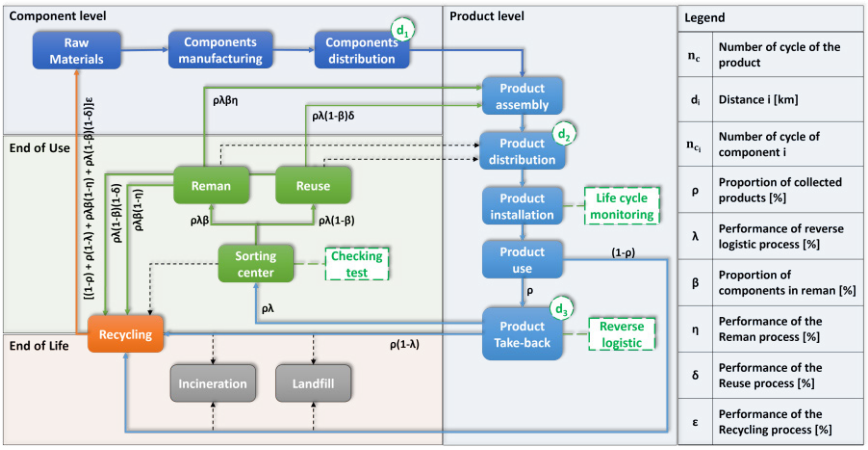

Fig. 1. Closed-loop circular product process with parameters

incineration and landfill. The closed-loop process begins with the extraction of raw materials to manufacture components, which are then transported to the assembly plant where the final product is assembled. This product is then transported to the distribution center and to the end-user, where it is installed. It is used for a certain period of time before being recovered through reverse logistics. The reverse logistics process involves the dismantling of the product at the premise of the end-user and the supply chain back to the assembly plant. After visual inspection, the product will be directed either to the recycling process, or to the sorting center where it is disassembled. Depending on the state of health of its components, these are either remanufactured or directly reused spare parts to refurbish a product. The Fig. 1 summarizes the closed-loop process with parameters.

In this type of circular process with many alternatives, allocation is sometimes inevitable. In line with the ISO 14040 standard on LCA recommendations, allocation should be avoided whenever possible. In this way, the definition of closed-loop process boundaries helps to avoid allocations.

To be able to simulate different alternatives, parameters was defined for each stage of the circular life of the product. These parameters are the performance in terms of efficiency of reverse logistics, reuse, remanufacturing and recycling. In addition, there are parameters for the proportion of used products collected and proportion of components in remanufacturing. The choice to use performance of processes as a parameter was made not only to simplify the model, but also to assess the impact of process efficiency in circularity. Each process has different factors that can influence its performance. For example, at the reverse logistics stage, dismantling time, transport mode, facility location, planning, etc. are all variables likely to influence process performance. [16,17]. In addition, the different distances of transportation have been considered: the distance (d_1) of the transportation of components from their manufacturing facility to the assembly plant; the distance (d_2) of the transportation of the product to the distribution center and to the end-user; and the distance (d_3) from the premise of the end-user to the assembly plant.

Among the parameters that are inputs for the simulation, the component proportion parameter in remanufacturing (ρ) is obtained based on the SoH value of the components. Wandji et al. have proposed a general framework for assessing the SoH of a complex system and SoH threshold intervals to be considered for optimal component remanufacturing [15,18]. Thus, the parameter (ρ) is the ratio of the number of components whose SoH value lies within the SoH threshold interval to the total number of components in the product.

4.2. Definition of formulas for calculating EI per unit of use

The formula to quantify the EI at each process step level per unit of use is the product of the EI of each process by its parameter factor. The EI of a process is obtained using a LCA software. Basically, it is the conversion of cumulative elementary flows of the process in an impacts categories using the PEF EF 3.0 method [19]. For the transport stage, the EI is obtained for a distance of 1 km, making it possible to simulate different distances for CS. The Table 1. summarizes the formulas for calculating the EI at each step of the closed-loop process, based on the process flow model in Fig. 1.

Table 1. Formulas for calculating EI.

N° of steps	Step of closed-loop process	Formula for calculating EI at each step.
1	Extraction of raw materials	$EI_{R-mat} = \sum_{i=1}^{n} EI_{mat_{Component_i}} \times \left(\frac{1+(n_{c_i}-1)\left[1-\left[(1-\rho)+\rho(1-\lambda)+\rho\lambda\beta(1-\eta)+\rho\lambda(1-\beta)(1-\delta)\right]\varepsilon\right]}{n_{c_i}}\right)$
2	Manufacturing of components	$EI_{man_{Components}} = \sum_{i=1}^{n} EI_{man_{Component_i}}$
3	Distribution of components	$EI_{dist_{components}} = \sum_{i=1}^{n} EI_{dist_{Component_i}} \times d_1$
4	Assembly of the product	$EI_{ass} = EI_{ass_{product}} \times \left(\frac{1+(n_c-1)[1-(\rho\lambda\beta\eta+\rho\lambda(1-\beta)\delta)]}{n_c}\right)$
5	Distribution of the product	$EI_{dist_{product}} = EI_{dist_{product}} \times d_2$
6	Installation of the product	$EI_{Inst} = EI_{inst_{product}}$
7	Use phase of the product	$EI_{use} = EI_{use_{product}}$
8	Take-back phase of the product	$EI_{take-back} = \left(\frac{(n_c-1)\times(\rho)}{n_c}\right) \times EI_{take-back_{product}} \times d_3$
9	Remanufacturing of components	$EI_{reman} = \sum_{i=1}^{n} EI_{reman_{Component_i}} \times \left(\frac{(n_{c_i}-1)\times(\rho\lambda\beta)}{n_{c_i}}\right)$
10	Reuse of components	$EI_{reuse} = \sum_{i=1}^{n} EI_{reuse} \times \left(\frac{(n_{c_i}-1)\times[\rho\lambda(1-\beta)]}{n_{c_i}}\right)$
11	Recycling of product and components	$EI_{recy} = \frac{\left[EI_{recy_{EoU}}\times(n_{c_i}-1)[\rho(1-\lambda)+\rho\lambda\beta(1-\eta)+\rho\lambda(1-\beta)(1-\delta)]\right]}{n_{c_i}} + \frac{\left[EI_{recy_{EoL}}\times[1+(n_c-1)[1-(1-\rho)]]\right]}{n_c}$
Total EI of the process		$\mathbf{EI_{Total} = \sum_{j=1}^{11} EI_j}$

The total EI is the sum of the EI calculated at each step of the process. These formulas are used to simulate scenarios that define the CS for different use case of the product.

4.3. Use case and scenarios

In a linear economy, whether B2B or B2C, products are used in different environments. The same product may be used in a building, a wind turbine or a solar installation, all of which have different conditions of use. Certain stages of the closed-loop process may therefore change, such as the use phase and the take-back phase. Product use cases can have an influence on the EI of the product. They are therefore taken into account in this paper.

In addition, two scenarios have been defined in order to compare the CSs. The scenario zero (Sc_0) is the baseline scenario in which, for two life cycles, two new products are used and then disposed at their EoL or EoU. The other is the circular scenario (Sc_1), in which a new product is used during the first life cycle. It is then recovered for refurbishment and used in the second life cycle. Refurbishment follows the closed-loop process shown in section 4.1. The Fig. 2 illustrates these two scenarios.

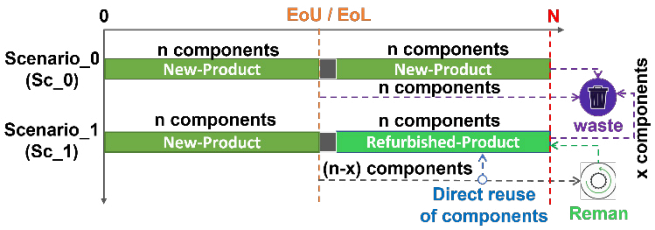

Fig. 2. Two Circular Scenarios for simulation

The following assumptions have been made for the simulation:

- In the scenario_0, the product is disposed and treated as waste at its EoL or EoU.
- In scenario_1, the refurbished product in the second life cycle comes from the new product in the first life cycle. The time of refurbishment is not taken into consideration.

These assumptions and the method described in this section are applied to a circuit-breaker use case.

5. Electric circuit-breaker use case

The electric circuit-breaker studied is an electrical protection device made up of 19 components, as shown in Table 2. It is used in a wide range of applications. In this application, its uses in wind turbines, solar energy and buildings are taken into account for the simulation. In these three applications areas, the product is subject to different conditions. Hence, it will not have the same lifetime. The lifetime is 2 years in wind turbines, 5 years in solar power and 15 years in buildings. For the CS simulation, the number of cycles for each component is defined for the two scenarios presented in section 4.2 and in the three application areas selected above (wind power, solar energy and buildings). They are illustrated in Table 2.

Table 2. Number of components cycles (n_{ci}) per scenario and use case.

		Wind turbine		Solar		Building	
N°	Components	Sc_0	Sc_1	Sc_0	Sc_1	Sc_0	Sc_1
1	Mobile Contact	1	2	1	2	1	2
2	Fixed Contact	1	2	1	2	1	2
3	Arc Chamber	1	2	1	2	1	2
4	Charging Motor	1	2	1	2	1	2
5	Clusters	1	1	1	1	1	1
6	Connection Terminal	1	1	1	1	1	1
7	Trigger Unit Base	1	1	1	1	1	1
8	Trigger Unit	1	1	1	1	1	1
9	Coils	1	2	1	2	1	2
10	Sensors	1	1	1	1	1	1
11	Filerie (Electrical Cable)	1	2	1	2	1	2
12	Housing And Accessories	1	1	1	1	1	1
13	Plastron	1	1	1	1	1	1
14	Mechanism	1	1	1	1	1	1
15	Pole Shaft	1	1	1	1	1	1
16	Mechanism Chassis	1	2	1	2	1	2
17	Chassis base	1	1	1	1	1	1
18	Auxiliary contacts	1	1	1	1	1	1
19	Others accessories	1	2	1	2	1	2
	Product	1	2	1	2	1	2

Closed-loop process parameters are also defined for the two scenarios defined in section 4.2 and for the three selected application areas. The wind turbine is assumed to be 900 km by truck from the assembly plant, the solar 500 km and the building 350 km. The refurbished product is also manufactured in the assembly plant. They are illustrated in Table 3.

Table 3. Parameters by scenario and use case.

		Wind turbine		Solar		Building	
Symbols	Parameters	Sc_0	Sc_1	Sc_0	Sc_1	Sc_0	Sc_1
N	Total Life cycle [Year]	4	4	10	10	30	30
n_c	Number of cycles of the product	1	2	1	2	1	2
d_1	Distance to the assembly plant	2000	2000	2000	2000	2000	2000
d_2	Distance to the distribution center and to the end-user	900	900	500	500	300	300
d_3	Distance of the reverse logistic	900	900	500	500	300	300
ρ	Proportion of collected products [%]	0	80	0	60	0	40
λ	Performance of the reverse logistic process [%]	0	70	0	50	0	20
β	Proportion of components in remanufacturing [%]	0	42	0	47	0	42
η	Performance of the Reman process [%]	0	80	0	80	0	80
δ	Performance of the Reuse process [%]	0	80	0	80	0	80
ε	Performance of the Recycling process [%]	70	70	70	70	70	70

6. Results analysis and discussion

This section is structured in different analysis points. In this analysis, it is assumed that components with a SoH value of between 50% and 70% should be remanufactured, and those with a SoH value of between 70% and 80% should be reused.

The first analysis point is the identification of the main contributors. In Fig. 3-a It has been found that the manufacturing and use phases in the wind turbine area are the main contributors in Sc_0. Therefore, in Sc_1, with parameters

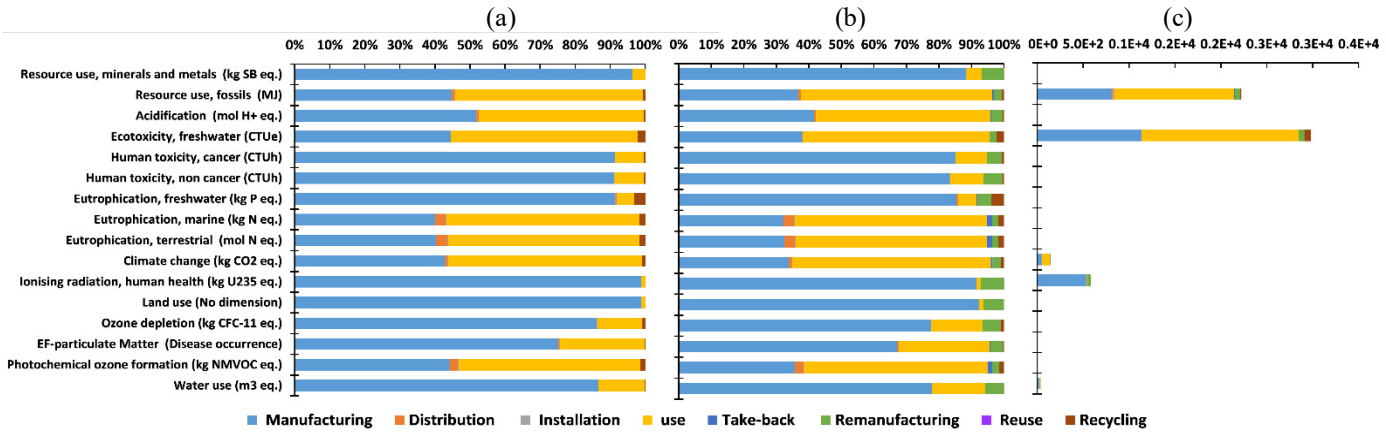

Fig. 3. (a) 100% stacked bar of the EI of a circuit-breaker in Sc_0; (b) 100% stacked bar of the EI of a circuit-breaker in Sc_1; (c) Stack bar of the circuit-breaker.

ρ, λ, β, η, δ and ε set at 50% and a remanufacturing of 9 components out of 19 (i.e., 47%), the main contributors are the same. However, with those parameters set to 100% and 47% of components in the remanufacturing process, it was found in Fig. 3-b. that the remanufacturing phase is the third contributor. These main contributors are the same for the other use cases.

The second point of analysis is the identification of the impact categories most concerned. It has been found in Fig. 3-c that ecotoxicity, freshwater; resource use, fossils; ionizing radiation, human health and climate change are of the greatest concern, whatever the use case.

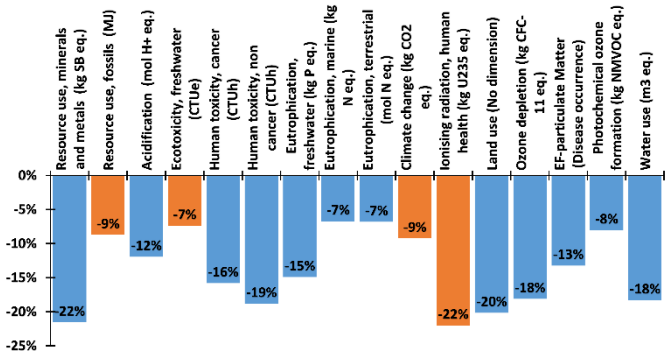

Fig. 4. Relative deviation of Sc_1 from Sc_0 for wind turbine application

According to Fig. 3-c, the circuit breaker has the greatest impact in the ecotoxicity category, freshwater, which poses a problem for aquatic species. The resource use category, fossil fuels, is also affected, which can disrupt hydrocarbon formation. Human health is also affected, as the manufacture and use of this product also generates impacts in the ionizing radiation, human health and climate change categories. Circularity is one of the keys to reducing these impacts, and the parametric LCA method fosters it. The third analysis point shows the influence of parameters in a LCA analysis.

To demonstrate this, the relative deviation of Sc_1 compared to Sc_0 under the same conditions has been calculated with parameters ρ, λ, β, η, δ and ε set at 100% and 47% of components remanufactured. The result shows a minimum EI reduction of 7% and a maximum of 22% in all impact categories. Focusing on the impact categories of greatest concern identified earlier, EI in the ionizing radiation (human health) category was reduced by 22%, the EIs in the climate change and fossil resource use category were reduced by 9%, and EI in the ecotoxicity (freshwater) category was reduced by 7%. Moreover, the EIs for the categories Resource use, minerals and metals; Human toxicity, non-cancer; Land use; Ozone depletion and Water use have been reduced by at least 18%. Fig. 4 sums it all up for wind turbine application. In addition, Fig. 5 shows the difference between the relative deviation of Sc_1 from Sc_0 with parameters set at 50% and that with parameters set at 100% for the all use cases.

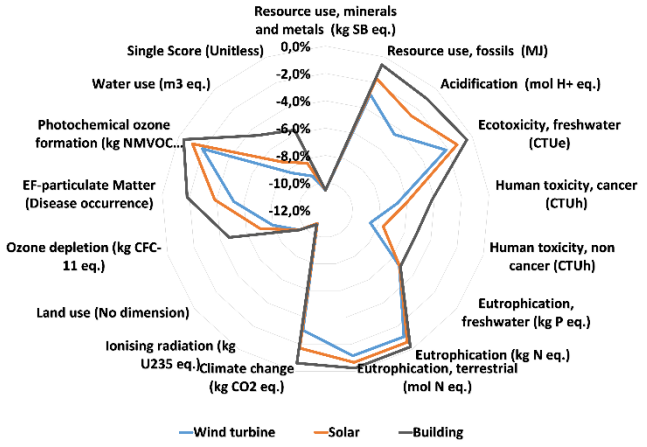

Fig. 5. Relative deviation with 50% to 100% parameters variation

In Fig. 5, it is observed that the relative deviations are all negative, meaning that varying the parameters from 50% to 100% reduces the EI in all impact categories. However, this relative deviation does not change from one use case to another for certain categories such as: Resource use, minerals and metals; Eutrophication, fresh water; and others. For other categories, on the other hand, it has been reduced from application for wind turbines to application for buildings. In the climate change category, for example, the relative difference is -3.1% for wind turbines, -1.7% for solar energy and -0.6% for buildings. This reduction is due to the operating conditions and lifetime of the circuit-breaker in these different applications. This implies that there is a limit at which the effort to extend product life no longer produces any significant environmental change. This analysis proves the influence of process performance parameters in generating process impacts.

Finally, this last point of analysis shows a simulation of three Sc_1 CS based on 47% remanufacturing of components under the conditions defined in Table 3 for the wind turbine application. In the first CS of Sc_1, the 47% are remanufactured, in the second they are all reused and in the last CS of Sc_1, there are 26% remanufactured and 21% reused out of the 47% upgraded. Fig. 6 shows that Sc_1 with 47% reuse components, has the lowest impact likely 10% less than the others for the climate change indicator. With the exception of ecotoxicity, one of the categories of greatest concern, where this Sc_1 is the second least polluting. This strategy is also the most advantageous because the EI of the reuse process is lower than the EI of the remanufacturing process. This analysis shows more or less the same result in the other use cases.

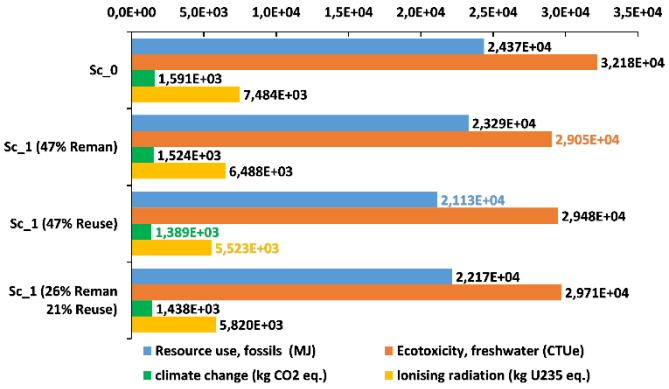

Fig. 6. Comparison of CS by scenario.

Finally, the proposed method has allowed the industrial partner to choose among three scenarios the one (Sc_1 with 47% reuse) which is optimal in terms of EI. The industrial partner has confirmed that this decision would be ambiguous to make without the simulation tool of the proposed method.

7. Conclusion

The parametric LCA method is effective for finding the CS with the lowest EI. It is useful for optimizing decision-making on the CS of a product in different use cases. It is based on performance parameters of circular value chain processes and product SoH. However, for optimal use, prior work must be carried out to assess the SoH of the product and its components, and to define with the manufacturer the values of the input parameters for the simulation.

The application of parametric LCA to the use case of an electrical circuit breaker first enabled us to simulate different SoH scenarios by varying the parameters and the number of components recovered for circular processes. Secondly, it showed that the CS of Sc_1, which consists in reusing 47% of recovered components, is the optimal strategy in environmental terms for the wind turbine application. This Sc_1 showed 10% less EI on average than the other scenarios for the climate change indicator. This decision would be ambiguous to make without the simulation tool based on the proposed method.

Future work will involve adding a life-cycle cost analysis (LCC), studying the CS of product transversality from one application area to another, and comparing it with others.

Acknowledgements

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References

[1] European Environment Agency. The European environment-state and outlook 2020 Knowledge for transition to a sustainable Europe, Publications Office of the European Union, Luxembourg: 2019.
[2] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. Resour Conserv Recycl 2017;127:221–32..
[3] Gehin A, Zwolinski P, Brissaud D. Integrated design of product lifecycles—The fridge case study. CIRP J Manuf Sci Technol 2009;1:214–20..
[4] Sutherland JW, Adler DP, Haapala KR, Kumar V. A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production. CIRP Annals 2008;57:5–8.
[5] Harter H, Singh MM, Schneider-Marin P, Lang W, Geyer P. Uncertainty Analysis of Life Cycle Energy Assessment in Early Stages of Design. Energy Build 2020;208:109635.
[6] Gehin A, Zwolinski P, Brissaud D. Towards the Use of LCA During the Early Design Phase to Define EoL Scenarios. In: Takata S, Umeda Y, editors. Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, London: Springer London; 2007, p. 23–8.
[7] Yu S, Zhang R. Life Cycle Assessment in Different Product Design Stages - A Coffee Pot Case Study. Applied Mechanics and Materials 2010;34–35:988–94.
[8] Miyoshi S, Segawa T, Takii M, Imamura T, Sakurai H, Kurosawa Y, et al. Evaluation of circularity of components for life cycle design: A toner bottle case study. Procedia CIRP 2022;105:267–72.
[9] He Y, Zhang J, Wang X, Li Y, Tian X, Wang Y. A process scenario oriented Life Cycle Assessment framework for machining processes. Procedia CIRP 2022;105:332–8.
[10] Tao F, Kishita Y, Scheller C, Blömeke S, Umeda Y. Designing a Sustainable Circulation System of Second-life Traction Batteries: A Scenario-based Simulation Approach. Procedia CIRP 2022;105:733–8.
[11] Zheng H, Li E, Wang Y, Shi P, Xu B, Yang S. Environmental life cycle assessment of remanufactured engines with advanced restoring technologies. Robot Comput Integr Manuf 2019;59:213–21.
[12] Pérez-Martínez MM, Carrillo C, Rodeiro-Iglesias J, Soto B. Life cycle assessment of repurposed waste electric and electronic equipment in comparison with original equipment. Sustain Prod Consum 2021;27:1637–49.
[13] Luis Amaya Rivas J. Assessment of the environmental benefits provided by closed-loop strategies for industrial products. University of Grenoble, 2012.
[14] Ijassi W, Rejeb H Ben, Zwolinski P. Environmental Impact Allocation of Agri-food Co-products. Procedia CIRP 2021;98:252–7.
[15] Wandji C, Rejeb H Ben, Zwolinski P. Characterization of the state of health of a complex system at the end of use. Procedia CIRP 2022;105:49–54.
[16] Zhang X, Zou B, Feng Z, Wang Y, Yan W. A Review on Remanufacturing Reverse Logistics Network Design and Model Optimization. Processes 2022, Vol 10, Page 84 2021;10:84.
[17] Taddei E, Sassanelli C, Rosa P, Terzi S. Circular supply chains in the era of industry 4.0: A systematic literature review. Comput Ind Eng 2022;170:108268.
[18] Wandji C, Riel A, Rejeb H Ben, Zwolinski P. Characterization of the State of Health of Electronic Devices for Fostering Safety and Circular Economy. In: Yilmaz M, Clarke P, Messnarz R, Wöran B, editors. Systems, Software and Services Process Improvement, Cham: Springer International Publishing; 2022, p. 148–60.
[19] Zampori L, Pant R. Suggestions for updating the Product Environmental Footprint (PEF) method. EUR 29682 EN, Publications Office of the European Union, Luxembourg: 2019.