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RESEARCH ARTICLE

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Analysis of parameters about useful life extension in 70 tools and methods related to eco-design and circular economy

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Abstract

One of the approaches followed by the circular economy (CE) to achieve sustainability through design is product life extension. Extending the life of products to make them useful for as long as possible is a means to reduce waste production and materials consumption, as well as the related impacts. For designers, conceptualizing products in a way that allows them to be used for longer is a challenge, and assessing how well they extend their lifespan can be helpful when it comes to choosing the best proposal. In this paper, 70 tools and methods related to eco-design and circular economy are studied to determine how many of them consider parameters related to life extension and which can be applied in the early stages of design. The results of the analysis show that most of the existing tools and methods are applicable to developed products, and only a few of them take into account parameters related to extending the useful life. Of the 70 tools and methods, only 14 include some parameter related to life extension and are applicable to concepts. CE toolkit, Eco-design PILOT, CE Designer, Circularity Assessment tool, Circularity Potential Indicator and Circular Design Tools take into consideration eight or more parameters to assess life extension in concepts. This will help designers select the most appropriate and will indicate the need for more complete tools to consider useful life extension in the early stages of design and thus enhance the selection of more sustainable products.

KEYWORDS
circular economy, conceptual design, eco-design, industrial ecology, product design, useful life extension

1 | INTRODUCTION

In recent decades, taking the sustainability of products into account has become increasingly important. The linear model of extraction–production–use–disposal and energy flow (often described as take–make–waste) is unsustainable (Frosch & Gallopoulos, 1989). In contrast, the circular economy (CE) provides an economic system with an alternative model of production and consumption (Beaulieu, 2015; Ellen MacArthur Foundation, 2015; Ellen MacArthur Foundation & McKinsey Center for Business & Environment, 2015) with multiple political implications (Cordella et al., 2019, 2020). The term CE appeared in the 1970s (Stahel & Reday-Mulvey, 1977) but it was not until 2013 that the Ellen MacArthur Foundation made it more popular. The concept of CE aims to minimize waste by facilitating recycling, remanufacturing, and reuse in order to maintain the added value of products for as long as possible (Evans & Bocken, 2014). Recent studies have analyzed material efficiency and waste management strategies (Cordella, Alfieri, Sanfelix et al., 2020). The circular economy is considered an interesting and important approach to help reduce global sustainability stress (European Commission, 2015; Ellen MacArthur Foundation, 2013). Included in the concept of CE there is also a need to combine product and service design strategies in order to keep the function and value of products, components, and materials at their best possible level (Bocken et al., 2016). Hollander et al. (2017) considered the fundamental differences between concepts such as eco-design and circular design. The CE also seeks to maintain the economic and environmental value of materials for as long as possible. To this end, it considers extending the service life of manufactured products and reuse. In this way, waste is eliminated, as materials and products can be reused and recycled indefinitely. It proposes a redefinition of the useful life of the product and introduces new terms like previous resource and recovery horizon (Hollander et al., 2017).

Circular design focuses on three approaches (Bocken et al., 2016): design to slow loops, thereby extending the useful life of products and components; design to close loops, which aims to favor the circular flow of material; and narrowing loops by doing more with less. In addition, Blomsma et al. (2019) recently proposed different innovation strategies such as reinventing, rethinking and reconfiguring, recirculating and, finally, restoring, reducing, and avoiding (material and product).

The aim of slowing loops or prolonging or intensifying the extension of the useful life of products is to slow down the flow of resources in order to decrease the environmental impact and increase social and economic value (Box, 1983; Roy, 2000). For Mukherjee et al. (2017) the useful life of a product "is the duration of time period in which the items remain useful to the customer." Design to slow loops intends to reduce the use of resources by extending the period of use of products through design for long-life and product life extension. Design for product life extension, as considered in CE includes technical aspects of the product such as reuse, maintenance, repair, technical upgrading or their combination, in addition to emotional aspects like attachment and trust, and reliability and durability (Bocken et al., 2016).

There are multiple design strategies to slow loops (useful life extension), some of which may appear integrated depending on their definition. This study has used the classification put forward by Bakker, den Hollander et al. (2014), who proposed the following:

- Design for attachment and trust: designing products that generate strong emotional bonds so as to easily produce attachment with the user (emotional durability) (Chapman, 2015). For Bocken et al. (2016), it involves creating products that are desired, liked, or relied upon for a longer time.
- Design for reliability and durability: designing products with high resistance to wear and tear, which operate over a given period of time without failure (Bakker, den Hollander, et al., 2014; Van den Berg & Bakker, 2015). According to Cordella, Alfieri, Clemm et al. (2021) "the durability of a product can be limited for technical reasons (e.g., time, cycles, distance) and depends on the resistance of the product to loads and degradation mechanisms (reliability), and the ability to bring it back to a functional state (through repair) once a limiting state is reached."
- Design for ease of maintenance and repair: keeping the product in optimal condition by preserving and repairing its functional capabilities (maintenance) and restoring it to a good state after damage (repair) (Bakker, Wang, et al., 2014; Bocken et al., 2016).
- Design for upgradability and adaptability: designing the product so that even if conditions change it remains useful (Linton & Jayaraman, 2005).
- Design for standardization and compatibility: making it easy to exchange parts that can be adapted to different products (Bakker, den Hollander, et al., 2014).
- Design for dis- and reassembly: guaranteeing that products and parts can be easily removed and reassembled (Bakker, den Hollander, et al., 2014).

According to Murakami et al. (2010) "product life extension is the concept of a product's lifespan, which is defined as the period from product acquisition to discarding of the product by the final owner." There are different reasons to discard products prematurely (technical bugs, new functionalities, aligning with fashion trends, etc.) (European Environment Agency, 2017). Failure to adapt to the user's future needs are some of the causes (Royo et al., 2021; Van Nes & Cramer, 2005), if their design does not consider technical upgrades and performance (Linton & Jayaraman, 2005) or, finally, if the user discards them prematurely even though they work (Mugge et al., 2005, 2010; van Weelden et al., 2016).

Regarding the design process, conceptual design is one of the most important tasks in engineering product development (Wang et al., 2002). In this phase, abstract ideas are developed by using approximate representations (Takala, 1989). Potentially relevant ideas and concepts are generated and developed during the ideation phase (Briggs & Reinig, 2007). Bocken et al. (2011) defined eco-ideation as the stage in which ideas with high potential to reduce environmental impact are generated (Tyl et al., 2014). The integration of the circular economy in the early stages of the product design process is important; it is difficult to introduce modifications once resources, infrastructures, and activities have been committed to a given design (Bocken et al., 2014). According to Kulatunga et al. (2015) and Lewis and Gertsakis (2001), 80% of the environmental impact of a product is determined in the early stages of design. These early design decisions will allow the development of products aligned with circularity principles. On the other hand, according to Bovea and Pérez-Belis (2012), there are two key factors that are needed to achieve sustainable design: the integration of environmental aspects early in the design process, and a multi-criteria approach to balance environmental and other traditional requirements (cost, safety, functionality, etc.). Moreover, Aguiar et al. (2022) analyzed the circular design strategies used throughout the literature, as well as the main barriers to their adoption, indicating that most articles on circular product design focus on the planning and concept development phases of the new product development process. Environmental concerns are systematically introduced during product design and development through eco-design (AENOR, 2003). Since the 1990s, companies have been trying to reduce the environmental impacts of products throughout their life cycle by integrating environmental considerations into product design (eco-design and design for the environment) (De Pauw et al., 2014; Stevels, 2007). Eco-design looks at key factors to meet environmental sustainability requirements in the most efficient and appropriate way possible (Tukker et al., 2001). Tischner et al. (2000) considered eco-design to mean environmentally aware product development, included within the concept of sustainable design. Important strategies that facilitate including the principles of the CE in product design can be applied based on eco-design. In the industrial field, eco-design considers and integrates environmental aspects in the product development process (ISO, 2011) by applying strategies designed to reduce the negative environmental impact throughout the product life cycle phases (Rossi et al., 2016). Product design strategies to slow resource loops include design for long-life products and design for product life extension, which are also eco-design strategies (Holt & Barnes, 2010).

The interest in this topic has driven the development of a large number of eco-design tools and methods to facilitate the integration of environmental aspects into the product development process (Baumann et al., 2002; Byggeth & Hochschorner, 2006) and to assist designers with their tasks (Ritzén, 2000). These tools are a systematic means to address environmental issues during the product development process (Baumann et al., 2002).

There are studies that look at different aspects of eco-design tools. For example, Tyl et al. (2014) conducted a comparative study of tools and methods focused on the eco-design process. Byggeth and Hochschorner (2006) compared 15 tools by analyzing their purpose, environmental perspective, type of outcome, and whether the tool allows evaluation of the results obtained. Rossi et al. (2016) and Rousseaux et al. (2017) studied the barriers that limit the effective implementation of tools in companies. Bovea and Pérez-Belis (2012) reviewed and classified tools that assess environmental product requirements and facilitate their integration into the design process.

From a CE perspective, there are no standardized methods to measure circularity in products (European Environment Agency, 2016) or approaches to assess the circular economy aspects of products (Cordella et al., 2018, 2021), although there are different metrics to assess how circular a product is or the potential to improve circularity (Lindgreen et al., 2020; Mesa et al., 2018; Parchomenko et al., 2019; Ruiz-Pastor et al., 2019; Saidani et al., 2019; Vinante et al., 2021). Pigosso et al. (2015) indicated that there is a growing interest in the development of eco-design tools and methods. In a recent analysis Schäfer and Löwer (2020) noted that the pressure on companies to adopt eco-design is also growing. Furthermore, there is the intention to generate tools for the early stages of the product development process (Jeswiet & Hauschild, 2005) and tools for industrial designers (Lindahl & Ekermann, 2013), among others.

Previous studies that analyzed the applicability of circularity measurement metrics in the conceptual phase of product design pointed out that the application of tools is based on an estimation of results that are not precise. These could be, for example, the weight and cost requirements, which are difficult to know in the initial phases of design (Ruiz-Pastor et al., 2019). These tools consider different aspects of circularity strategies. Nonetheless, they fail to take into account specifically how to improve the product life extension. For Bakker, Wang et al. (2014), product life extension could help to solve one of the major problems of the last decade in industrialized societies, which is the increase in material production and waste due to the decreasing shelf life of products (Huisman et al., 2012) and the high environmental impact of material production and processing (Allwood et al., 2011).

The main objective of this work is to study whether tools and methods are applicable in the initial phases of design and how they are applied, in terms of useful life extension, in order to help reduce this gap in the specific measurement of product life extension. To this end, the study analyzes how many parameters related to the extension of useful life they consider, how they are applied, and the type of result obtained. This will help designers to select, in the conceptual phase, the most appropriate tool or method to assess or to compare the life extension in different proposals. This will allow them to know which conceptual proposal best optimizes the lifespan in an accurate way, so that the future product will be developed with the longest possible lifespan. On the other hand, it will also serve to test whether current tools and methods consider design strategies for life extension in the same way and what needs to be improved. In addition, this study is a first insight into the development of a tool that would evaluate or compare the ideas generated for extending the useful life in the conceptual phases of design.

2 | METHODOLOGY

The desk research carried out is divided into two parts. The first presents an analysis of 70 tools and methods related to eco-design and circular economy to determine whether they take life extension into account and whether they are applicable for assessing concepts. The second part consists of a detailed analysis of what life extension strategies are considered by the tools that can be applied to design concepts.

2.1 | Part one: Analysis of tools and methods related to eco-design and circular economy

First, 70 tools and methods related to eco-design and circular economy were selected from the compilations presented by Bovea and Pérez-Belis (2012), together with the results of a search for more recent tools and methods (from 2012 onward). The search was structured using two different

TABLE 1 List of keywords used to identify the literature review

Related term		Category terms
Eco-design	&	Tool
Ecodesign		Tools
Circularity		Method
Circular economy		Methods
		Methodology
		Approach
		Approaches
		Metric
		Metrics

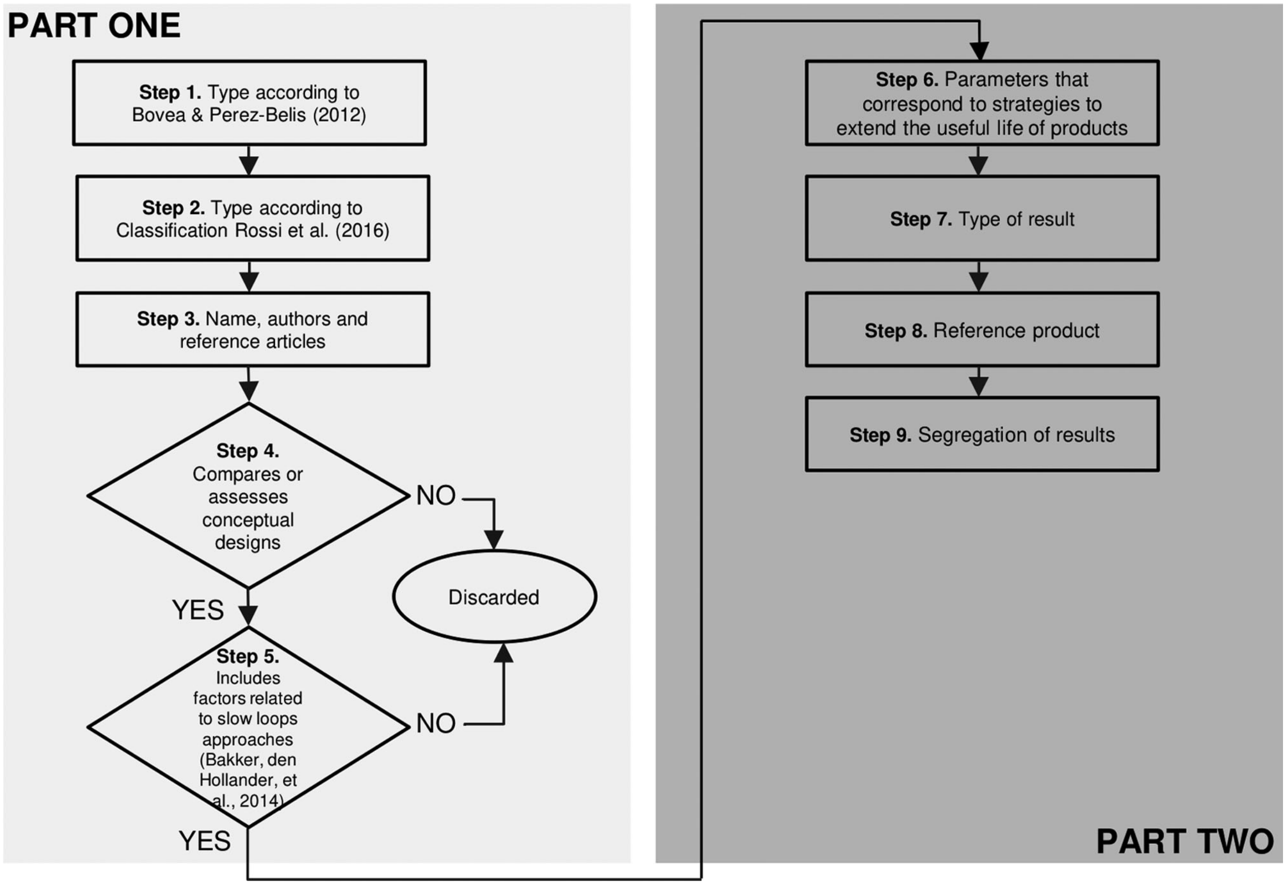

FIGURE 1 Methodology applied for the classification of methods and tools related to eco-design and circular economy

sets of keywords. The words "ecodesign," "eco-design," "circularity," and "circular economy" were related to different terms as shown in Table 1. Tools or methods published in 2012 or later were selected as search criteria. Among the results, all those presenting a clearly differentiated tool or method were selected. Regarding the circularity indicators (c-indicators), the study by Saidani et al. (2019) was taken into account. In this study they selected the Circular Economy Toolkit (CET) (Bocken & Evans, 2013), Circular Economy Indicator Prototype (CEIP) (Cayzer et al., 2017), and Circularity Potential Indicator (CIP) (Saidani et al., 2017a, 2017b) to evaluate circularity potential improvement during design and development processes.

The following information was identified and analyzed for each of them, with the step indicated in brackets following the scheme in Figure 1:

- Step 1. They are classified by type by identifying them according to the taxonomy of Bovea and Pérez-Belis (2012) as tools or methods.
  In the opinion of Jarzabkowski and Kaplan (2015) a tool is "a generic name for frameworks, concepts, models, or methods." A tool could include methods or frameworks, indicators and data, software, and web tools, which are used to help solve a problem. They offer models of causal structures, provide spaces for collecting data, and establish decision rules for selecting among alternatives, according to March (2006). The word

"eco-design tool" refers to "any systematic means for dealing with environmental issues during the product development process" (Baumann et al., 2002). Eco-design tools make it possible to define a common language and structure, and make the objectives visible to the different actors (Åkermark, 2003). According to Ritzen (2000, p. 10), "the main point is that eco-design tools are supposed to assist designers in their daily tasks, being 'artifacts that support product developers with certain considerations or tasks, typically arranged in software or written guidelines."

The concept of methodology refers to the procedures and prescriptions a practitioner must follow to achieve a certain goal with chronological steps (Pahl et al., 2007). Within this framework, tools can be seen as a system of techniques associated with a method, as well as a way of achieving objectives (Vallet et al., 2009).

For this study, a method will be considered a more global process that helps to analyze or understand a problem, while a tool will be understood as an instrument that helps or assists the researcher in a certain activity. These criteria have been applied for all other tools and methods that are not classified in their taxonomy.

- Step 2. Classification as a typology, into the following types according to Rossi et al. (2016): Life Cycle Assessment (LCA) (ISO, 2006) and Computer Aided Design (CAD) Integrated tools, which quantify the environmental performance of a product or service over its entire life cycle (Marosky et al., 2007); Diagram tools, which quantify environmental performances through more qualitative assessments; Checklists and guidelines, which consider the characteristics of the design, serve as a guide for designers when it comes to choosing the best solution and Design for X approaches (Huang, 1996). The latter optimize specific product requirements by focusing on a specific design goal. There are also methods that assist eco-design through a structured framework. These are, according to their main aim: methods for supporting the company's eco-design implementation and generation of eco innovation (Le Pochat et al., 2007); methods for integrating different existing tools, methods for implementing the entire life cycle and user-centered design for sustainability methods.

  The tools not covered in the study by Rossi et al. (2016) have been classified in each of the typologies according to their similarity to the characteristics of the tools.
- Step 3. Name, authors, and references. The full name of the tool or method, author(s), related publications, and links to the tool or method are identified.
- Step 4. Possibility of comparing or assessing conceptual designs. Conceptual designs are considered to be numerous product alternatives that meet the given functional requirements obtained in the conceptual design phase (Diaz et al., 2021). Conceptual designs are obtained in early design phases, where the description of the future product is abstract and no information on the final product attributes that determine its future environmental impact and life cycle properties is available (Dewulf et al., 2005; Lindahl, 2005).

  If it is not possible to compare or assess conceptual design, then the tool or methodology is discarded. The cases in which it is not possible to compare or evaluate concepts are as follows:
  - The method or tool is designed to be used on final or preliminary designs only (design phases in which the characteristics of the sketch or idea obtained in the conceptual phase are defined), as it requires data that are only known when the product is defined at a preliminary or detailed level (e.g., if the parameter considers the specific or estimated quantity and type of material used in the product design). Although other types of rapid analyses exist, such as Streamlined Life Cycle Analysis (SLCA) (Bennett & Graedel, 2000), no methods or tools that perform estimation have been considered in this study.
  - The method or tool helps to obtain other environmental issues not related to lifespan extension, but it does not evaluate or compare designs. This occurs only if it considers how well an idea or product performs environmentally but does not offer any help or guidance on assessing or comparing it with others. This is the case for checklists that only take into account the fact that the design uses materials and components correctly, but does not allow for the comparison or evaluation of solutions.
  - If it only supports the generation of innovative solutions, that is, if it helps to generate new creative ideas, but does not consider any comparison or assessment.
- Step 5. Parameters related to design strategies to extend the useful life. A parameter is defined as each of the variables considered by the tool or method to evaluate some aspect. For each parameter, an analysis is performed to determine whether it corresponds to design strategies to lengthen or extend the lifespan as defined by Bakker, den Hollander et al. (2014). The possible options in this case are shown in Table 2:

2.2 | Part 2: Analysis of tools and methods related to eco-design and circular economy that consider life extension and allow for the comparison and assessment of concepts

The tools and methods that have at least one parameter for extending the useful life and that allow for assessment of the conceptual design proposals were investigated in the second part of the research, while also analyzing the following aspects (Figure 1):

- Step 6. Type of design strategies to extend the useful life. All parameters that correspond to design strategies to lengthen or extend the useful life are categorized according to the classification of Bakker, den Hollander et al. (2014), following this coding:
  - S1. Design for attachment and trust

TABLE 2 Criteria for classifying tools and methods in steps 4 and 5 (Bakker, den Hollander, et al., 2014)

Metric	Definition	Criteria
Possibility of comparing or assessing conceptual designs (step 4)		
Metric	**Definition**	**Criteria**
NO	When it is not possible to compare concepts	If the tool or method is designed only to be used in final or preliminary designs, data are required that are only known when the product is defined at a preliminary or detailed level. It helps to obtain other environmental issues, but it does not evaluate or compare designs. It only supports the generation of innovative solutions.
YES	When it is possible to compare concepts	If the tool or method does not consider any of the above.
If it considers parameters related to design strategies to extend the useful life (step 5)		
Metric	**Definition**	**Criteria**
YES	When it contains parameters related to design strategies to extend useful life	If any parameter of the tool or method considers any of the design approaches in order to slow loops: Design for attachment and trust Design for reliability and durability Design for ease of maintenance and repair Design for upgradability and adaptability Design for standardization and compatibility Design for dis- and reassembly
NO	When it does not contain parameters related to design strategies to extend useful life	If the tool or method does not consider any of the above.
IT ALLOWS USER INPUT	If the parameters are entered by the user	If the criterion is not intrinsic to the tool or method but allows the designer to include it as a design requirement.
YES*	It considers parameters, but in a different way from the YES section	If extending the useful life is considered, but by means of an overall factor estimated by the designer.

- S2. Design for reliability and durability
- S3. Design for ease of maintenance and repair
- S4. Design for upgradability and adaptability
- S5. Design for standardization and compatibility
- S6. Design for dis- and reassembly

For instance, in the Ten Golden Rules method, which is of the "Checklist and guidelines" type, one of the parameters considered is RULE 3: "*Use structural features and high quality materials to minimize weight in products if such choices do not interfere with necessary flexibility, impact strength or other functional priorities*" (Luttropp & Lagerstedt, 2006, p. 1401). This parameter would be related to strategy "S2. Design for durability and reliability" because material minimization is dependent on the reliability and safety of the product (Grujicic et al., 2010). Furthermore, a parameter can also contain several strategies; for example, in the CE Designer tool, the parameter "Easy replacement of components" is related to S3. Design for ease of maintenance and repair, and S4. Design for upgradability and adaptability. This same identification was carried out for all the parameters of the tools and methods studied in the second phase.

- Step 7. Type of result. Whether the result obtained by the tool or method is qualitative or quantitative.
- Step 8. Reference product. Whether or not the tool or method uses a reference product for assessment or comparison purposes. "No comparison" must be ticked if no reference product is used, "Absolute comparison" if both the product under study and the reference product are assessed, and "Relative comparison" if the assessment of the product is performed in relation to the reference product.
- Step 9. The way in which the results are grouped. An assessment was carried out to determine whether the results obtained by applying the tool or method are presented separately (segregated) or whether they are grouped in a joint assessment (not segregated).

3 | RESULTS AND DISCUSSION

The following section shows the results corresponding to each of the two phases of analysis described above, respectively.

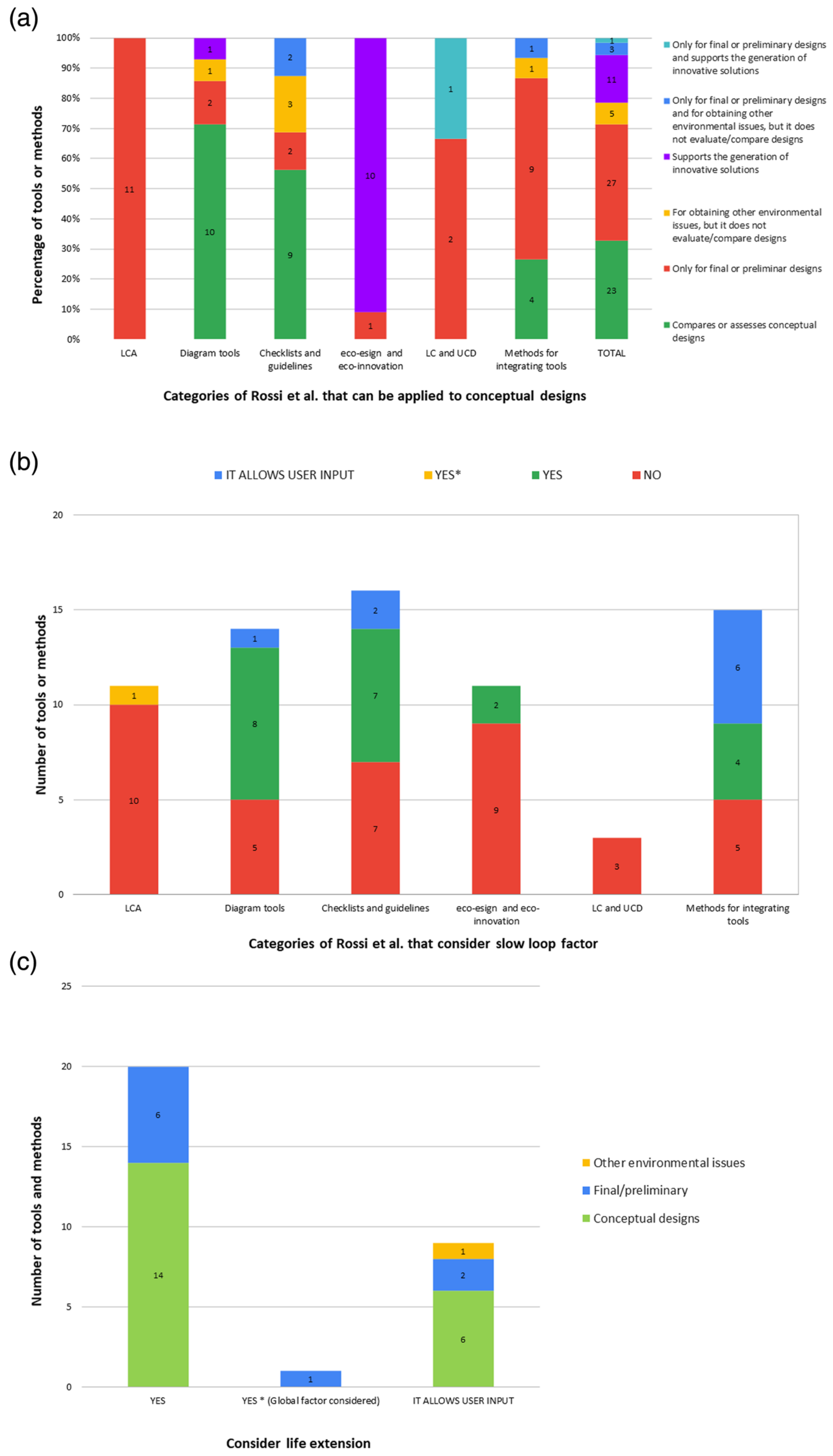

FIGURE 2 (a) Percentage of tools or methods according to the categories of Rossi et al. (2018) that can be applied to conceptual designs. (b) Number of tools according to the slow loop factors they consider per category (in absolute values). (c) Summary of tools and methods that consider extending the useful life according to whether or not they can be applied to conceptual designs. The underlying data for this figure can be found in Supporting Information S1.

3.1 | Classification of tools and methods related to eco-design and circular economy

Table 3 shows the 70 tools and methods analyzed in the study and the results obtained from the analysis of parameters. The results indicate that only 14 of the 70 tools and methods allow concepts to be assessed while considering criteria for extending the lifespan of products without the designer including it as a requirement.

Only 30% of the tools and methods analyzed allow comparison or assessment of conceptual designs (Figure 2a). Furthermore, these correspond to the categories (Section 2.1) of Diagram tools, Checklist and guidelines, and Methods for integrating tools. The Checklists and guidelines category contains the highest percentage of tools and methods (23%), followed by Methods for integrating tools (21%) and, finally, LCA and Methods for

TABLE 3 List of eco-design and circular methods and tools considered for the study

Nº	Type according to Bovea & Perez-Belis (2012)	Type according to Rossi et al. (2016)	Name	Authors and reference articles	Compares or assesses conceptual designs	Only for final or preliminary designs	For obtaining other environmental issues, but it does not evaluate / compare designs	Supports the generation of innovative solutions	Includes factors related to slow loops approaches (Bakker, Den Hollander, et al., 2014)
1	tool	LCA tools	Metric for quantifying the level of circularity of a product (CPM)	Linder et al. (2017)	NO	X			NO
2	tool	LCA tools	Ecolizer	http://www.ecolizer.be/design/new	NO	X			NO
3	tool	LCA tools	Eco-innovations process metric	López-Forniés et al. (2017)	NO	X			NO
4	tool	LCA tools	Eco-ideation process	Bocken et al. (2012)	NO	X			NO
5	method	LCA tools	Streamlined Life Cycle Assessment (SLCA)	Bennett & Graedel (2000)	NO	X			NO
6	method	LCA tools	Oil Point Method (OPM)	Bey, Lenau, and Larsen (1999), Lenau & Bey (2001), Bey (2000)	NO	X			NO
7	tool	LCA tools	Life Cycle Assessment (LCA)	ISO 14006 (2006)	NO	X			NO
8	method	LCA tools	Pre-LCA tool	Tolle et al. (1994)	NO	X			NO
9	tool	LCA tools	Materials Energy Chemicals Other (MECO)	Wenzel et al. (2000) ; Pommer et al. (2001)	NO	X			NO
10	method	LCA tools	MET-matrix	Brezet & van Hemel (1997); Byggeth & Hochschorner (2006)	NO	X			NO
11	method	LCA tools	Circularity Calculator (evolution of MCI)	Foundation & Granta Design (2015) http://www.circularitycalculator.com/	NO	X			YES*
12	tool	Diagram tools	Circular Economy Toolkit	Evans & Bocken (2014)	YES				YES
13	tool	Diagram tools	CE Designer	*CE Designer* (2019)	YES				YES
14	tool	Diagram tools	Spidermap	Van den Berg & Bakker (2015)	YES				YES
15	tool	Diagram tools	Idea Evaluation Matrix (SInnDesign)	www.sinndesignproject.eu	YES				IT ALLOWS USER INPUT
16	tool	Diagram tools	LiDS Wheel	Brezet & van Hemel (1997)	YES				YES
17	tool	Diagram tools	Eco Functional Matrix (EFM)	Bhamra & Hon (2004)	NO	X			YES
18	tool	Diagram tools	House of Ecology (HOE)	Halog et al. (2001)	NO		X		NO
19	method	Diagram tools	ERPA Matrix	Graedel (1998); Graedel & Allenby (1996, 1998)	NO	X			NO
20	tool	Diagram tools	Eco-COMPASS	Fussler &James (1996)	YES				NO
21	tool	Diagram tools	Eco-ASIT	Turner (2009)	NO			X	NO
22	tool	Diagram tools	Econcept Spiderweb	Tischner et al. (2000)	YES				YES
23	tool	Diagram tools	Circular Economy Indicator Prototype (CEIP)	Cayzer et al. (2017)	YES				NO
24	tool	Diagram tools	Circularity Check	Circularity Check (2019)	YES				YES
25	tool	Diagram tools	Circularity Assessment tool	Technical University of Denmark (2020)	YES				YES
26	method	Checklists and guidelines	Ten Golden Rules	Luttropp & Lagerstedt (2006)	YES				YES
27	method	Checklists and guidelines	Eco-design PILOT	Wimmer & Züst (2003) http://pilot.eco-design.at/pilot/ONLINE/ESPANOL/PDS/DETAILS/712A.HTM	YES				YES
28	tool	Checklists and guidelines	Requirements matrix	Keoleian et al. (1995)	NO		X		NO
29	method	Checklists and guidelines	AT&T checklist	Keoleian (1996)	NO		X		NO
30	method	Checklists and guidelines	KODAK checklist	Betz & Vogl (1996)	NO	X	X		NO
31	method	Checklists and guidelines	Fast Five Philips Awareness	Meinders (1997)	YES				YES
32	method	Checklists and guidelines	Eco-Design Checklist Method (ECM)	Wimmer (1999)	NO	X			YES
33	tool	Checklists and guidelines	AT&T matrix	Graedel (1998); Graedel & Allenby (1996, 1998)	NO	X			NO
34	tool	Checklists and guidelines	Volvo's Black List; Volvo's Grey List;	Nordkil (1998b, 1998a, 1998c)	NO	X	X		NO

(Continues)

TABLE 3 (Continued)

Nº	Type according to Bovea & Perez-Belis (2012)	Type according to Rossi et al. (2016)	Name	Authors and reference articles	Compares or assesses conceptual designs	Only for final or preliminary designs	For obtaining other environmental issues, but it does not evaluate / compare designs	Supports the generation of innovative solutions	Includes factors related to slow loops approaches (Bakker, Den Hollander, et al., 2014)
			Volvo's White List						
35	tool		ABC-analysis	Tischner et al. (2000); Lehmann (1993)	NO		X		NO
36	tool		Dominance Matrix or Paired Comparison	Tischner et al. (2000)	YES				NO
37	tool		Eco-design Checklist	Tischner et al. (2000)	YES				YES
38	tool		Design Abacus	Bhamra & Lofthouse (2007); Lofthouse (2004)	YES				IT ALLOWS USER INPUT
39	tool		Circular Design Tool	Moreno et al. (2016)	YES				YES
40	tool		Circularity Potential Indicator (CPI)	Saidani et al. (2017b, a)	YES				YES
41	tool		A guidance for navigating trade-offs to support sustainability related decision-making	Kravchenko et al. (2020)	YES				IT ALLOWS USER INPUT
42	tool	Methods for supporting the company's eco-design implementation and generation of eco innovation	Product Ideas Tree (PIT) Diagram	Jones et al. (2001); Eckert et al. (2000)	NO			X	NO
43	tool		ASIT	http://www.asit.info Turner (2009); Horowitz (1999)	NO			X	NO
44	tool		Information-Inspiration	Lofthouse (2004)	NO			X	NO
45	tool		TRIZ- CONTRADICTION MATRIX	Chen & Liu (2003)	NO			X	NO
46	tool		TRIZ- final ideas Result	Jones (2003)	NO			X	NO
47	tool		TRIZ-nine screen	O'Hare (2010)	NO			X	NO
48	tool		TRIZ-CBR	Yang & Chen (2011)	NO			X	NO
49	tool		TRIZ-Eco Guidelines	Regazzoni & Russo (2008)	NO			X	NO
50	tool		TRIZ-LCP Planner	Kobayashi (2006)	NO	X			YES
51	tool		TRIZ-Eco-MAL'IN	Samet (2010)	NO			X	NO
52	tool		Circularity Deck	Konietzko et al. (2020)	NO			X	YES
53	method	Methods for implementing the entire LC and UCD for sustainability	Environmental Product Life Cycle Matrix (EPLC)	Gertsakis (1997)	NO	X			NO
54	method		Integrated Product and Process Development (IPPD)	Grüner & Birkhofer (1999)	NO	X			NO
55	method		Life Cycle PLANNING (LCP)	Kobayashi (2006)	NO	X		X	NO
56	tool	Methods for integrating different existing tools	Quality function development for environment (QFDE)	Masui et al. (2003)	YES				IT ALLOWS USER INPUT
57	tool		Environmental QFD (E-QFD)	Davidsson (1998)	NO	X			YES
58	tool		DFE matrix	Johnson & Gay (1995)	YES				YES
59	tool		Implementing DFE Strategies (RAILS)	Hemel (1995)	NO	X			YES
60	tool		Integrated Approach to Sustainable Product Development	Hanssen et al. (1996)	NO	X			IT ALLOWS USER INPUT
61	tool		Green-QFD (GQFD)	Bovea & Wang (2005); Cristofari et al. (1996); Dong et al. (2003); Mehta & Wang (2001); Zhang et al. (1999)	YES				IT ALLOWS USER INPUT
62	tool		Environmental Objective Deployment (EOD)	Karlsson (1997)	YES				IT ALLOWS USER INPUT
63	tool		Environmentally Conscious Quality Function Deployment (ECQFD)	Vinodh & Rathod (2010)	NO	X			IT ALLOWS USER INPUT
64	tool		Life Cycle Quality Function Deployment (LC-QFD)	Ernzer & Birkhofer (2005)	NO		X		IT ALLOWS USER INPUT
65	tool		Life Cycle Environmental Cost Analysis (LCECA)	Senthil Kumaran et al. (2001)	NO	X			YES
66	tool		Eco-Value Analysis (Eco-VA)	Oberender & Birkhofer (2004)	NO	X			NO
67	tool		Eco-Re-Design	Bovea & Wang (2005)	NO	X			NO
68	tool		Environmental Impact and Factor Analysis (EIFA)	Stanford University (1995)	NO	X			NO
69	tool		Environmental FMEA (E-FMEA),	Nielsson et al. (1998)	NO	X			NO
70	tool		Eco-FMEA	Dannheim et al. (1998)	NO	X	X		NO

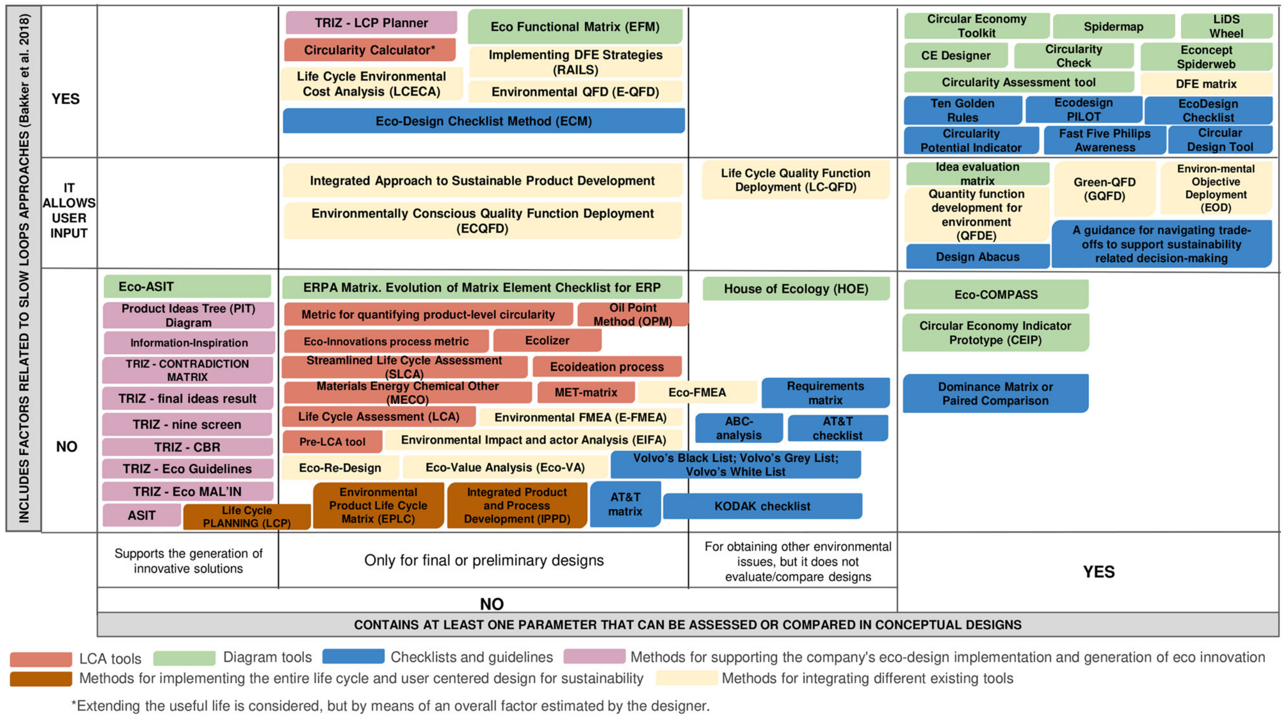

FIGURE 3 Status of each tool or method according to the results obtained from Table 3

supporting the implementation of the company's eco-design and generation of eco innovation, with 16%. Of all the tools and methods analyzed, 38% require final or preliminary designs in order to be able to assess or compare proposals.

Figure 2b shows the number of tools and methods that consider at least one parameter corresponding to design strategies in order to lengthen or extend the useful life according to the type of method or tool. Twenty-one of them contain at least one parameter related to extending useful life, as can be seen, although there is one that allows it by means of a global factor estimated by the designer (Circularity Calculator). Nine other parameters include the possibility of their being incorporated as a design requirement, thereby making a total of 30 methods or tools out of the 70 analyzed. None of the 21 that allow assessment of at least one parameter related to extending the useful life follow the line of LCA and life-cycle and user-centered design. The four categories that have tools and methods that consider extending the lifespan are Diagram tools, with eight, and Checklist and guidelines, with seven, followed by the category Methods for integrating tools with four and, finally, Eco-design and eco-innovation with two.

Finally, an analysis of the tools that consider life extension showed that only 14 of the 30 tools or methods allow its application to conceptual designs (Figure 2c). There are also three tools that, while allowing evaluation or comparison of conceptual designs, do not have any life extension parameters, although they could be included by the rater.

Lastly, Figure 3 shows the 70 tools and methods according to the two main criteria studied: the possibility of comparing or assessing concepts (horizontal axis) and the presence of parameters to lengthen or extend the useful life (vertical axis). This graph facilitates the selection of eco-design methods or tools for evaluating different concepts by taking into account the extension of the lifespan according to Bakker, den Hollander et al. (2014). The results show that no eco-design tools or methods help in the generation of ideas and also contain at least one parameter to lengthen or extend the useful life. As for the tools and methods that do allow the assessment or comparison of concepts, there are three that do not consider any parameter to lengthen or extend the useful life (Eco-COMPASS, CEIP, and Dominance Matrix or Paired Comparison). Idea evaluation matrix, Green-QFD, Design Abacus, quality function development for environment (QFDE), A guidance for navigating trade-offs to support sustainability related decision-making, and Environmental Objective Deployment are the six that only consider it if included by the rater (when the criterion is not intrinsic to the tool or method) and 14 do consider it. Of the 14 tools, 7 belong to the Diagram tools category (CET, Spidermap, CE Designer, LiDS Wheel, Circularity Check, Circularity Assessment tool, and Econcept Spiderweb), another 6 are in Checklist and guidelines (Eco-design PILOT, Ten Golden Rules, Fast Five Philips Awareness, Circular Design Tool, CIP, and Eco-Design Checklist) and the DFE matrix is included in Methods for integrating different existing tools.

3.2 | Selection of methods and tools that consider extending the useful life of products

Table 4 shows the 14 tools selected from Figure 3 organized according to the classification of Rossi et al. (2016) and analyzed according to the information described in the methodology. The most relevant information is found in the section Parameters, which describes strategies to extend

TABLE 4 Summary of tools and methods that consider useful life extension and help to evaluate or compare concepts

No.	Type	Type according to classification by Rossi et al. (2016)	Name	Authors	Parameters that correspond to strategies to extend the useful life of products	Type of result: QUANTITATIVE	Type of result: QUALITATIVE	Reference product: ABSOLUTE COMPARISON	Reference product: RELATIVE COMPARISON	Reference product: DOES NOT COMPARE	Segregation of results: SEGREGATED	Segregation of results: NOT SEGREGATED
12	TOOLS	**Diagram tools**	**Circular Economy Toolkit**	www.circulareconomytoolkit.org; Evans and Bocken (2014)	S2. Product failures are frequent S2. Product has a very long lifetime S3. Cost to repair is small in comparison to the product cost S3. Suitable maintenance/repair service already offered (could include repair, servicing, spare parts, diagnostics, technical support, installation, and warranty) S3. Easy to access internal workings S3. Simple workings, easy to understand S3. Components, connectors, modules, or leads are standardized S3. Easy to find fault		●			●	●	
13			**CE Designer**	https://www.katche.eu/knowledge-platform/tools-and-training-materials/katch_e-tools/ce-designer/	S1. Strong product-user relation S2. Durable and wear resistant materials and components S1. Timeless and customized design S2. Reliability S1. User-friendliness. The design of simple to use products results in their proper use and therefore contributes to a longer lifetime. S3. S4. Easy replacement of component S4. Aesthetic and/or technical upgradeability S4. Use of modular solutions S3. S4. Simplified product architecture S6. Choice of tools needed for dis- and reassembly S6. Facilitate access and detection of connecting elements S6. Minimize connecting elements S6. Standard connection elements	●		●				●

(Continues)

TABLE 4 (Continued)

No.	Type	Type according to classification by Rossi et al. (2016)	Name	Authors	Parameters that correspond to strategies to extend the useful life of products	Type of result: QUANTI-TATIVE	Type of result: QUALITA-TIVE	Reference product: ABSOLUTE COMPARISON	Reference product: RELATIVE COMPARI-SON	Reference product: DOES NOT COMPARE	Segregation of results: SEGREGATED	Segregation of results: NOT SEG-REGATED
14			**Spidermap**	Van den Berg and Bakker (2015)	S4. Future proof (timeless design/adaptable/ durable/roadmap fit) S3. Maintenance (lifetime prognostics/repair and upgrade/easy cleaning/difficult to service) S6. Disassembly (quick/easy/limited use and diversity of fasteners and tools/difficult)		●	●			●	
16			**LiDS Wheel**	Brezet and van Hemel (1997)	S2. Reliability and durability S3. Easy to maintain and repair S4. Modular product structure S1. Classic design S1. User taking care of product		●	●			●	
22			**Eco-concept Spider-web**	Tischner et al. (2000), Kleiber (2011)	S2. Longevity (longer lifetime)		●	●			●	
24			**Circularity Check**	Circularity Check (2019)	S2. S3. S6. S4. S1 Has the product or service been redesigned for prolonged product lifetime and/or improved functionality? (For improved product lifetime by quality, or for functionality/ for improved ease of maintenance/ for improve ease of repairs [easy access to the usage status, internal working and identification of the product, simple workings, easy to understand]/ product upgrading/ increase emotional attachment) S2. What increase in product lifetime and/or functionality have you achieved? S2. Is your product a durable item? S5. Do you offer and/or facilitate maintenance and/or repair of the product over the total lifetime? (On top of this, all components, connectors, modules, and leads are standardized)	●				●	●	

(Continues)

TABLE 4 (Continued)

No.	Type	Type according to classification by Rossi et al. (2016)	Name	Authors	Parameters that correspond to strategies to extend the useful life of products	Type of result: QUANTITATIVE	Type of result: QUALITATIVE	Reference product: ABSOLUTE COMPARISON	Reference product: RELATIVE COMPARISON	Reference product: DOES NOT COMPARE	Segregation of results: SEGREGATED	Segregation of results: NOT SEGREGATED
25			**Circularity Assessment tool**	Technical University of Denmark (2020)	S2. Focus mainly on functionality and quality performance S2. Think about activity supports in the operational stage S3. Make it easy to inspect the product and components S3. Make it easy to clean the product and components S3. Make exchanging of faulty components easily accessible S3. Make it easy to dismantle the product nondestructively S5. Design standardized components across different products and models S5. Design standardized tools required across different products and models S2. Use durable and robust components and materials S4. Design in modular construction S5. Make spare parts and exchanging components easily available S1. Consider timeless design, emotional attachment, and compatibility S6. Use joints and connectors that can be easily opened and closed multiple times	●	●	●			●	

(Continues)

TABLE 4 (Continued)

No.	Type	Type according to classification by Rossi et al. (2016)	Name	Authors	Parameters that correspond to strategies to extend the useful life of products	Type of result: QUANTITATIVE	Type of result: QUALITATIVE	Reference product: ABSOLUTE COMPARISON	Reference product: RELATIVE COMPARISON	Reference product: DOES NOT COMPARE	Segregation of results: SEGREGATED	Segregation of results: NOT SEGREGATED
26	METHODS	**Checklists and guidelines**	**Ten Golden Rules**	Luttrop and Lagerstedt (2006)	S2. RULE 3. Use structural features and high-quality materials to minimize weight in products if such choices do not interfere with necessary flexibility, impact strength or other functional priorities S3. S4. RULE 5. Promote repair and upgrading, especially for system-dependent products. (e.g., cell phones, computers, and CD players) S2. RULE 7. Invest in better materials, surface treatments or structural arrangements to protect products from dirt, corrosion, and wear, thereby ensuring reduced maintenance and longer product life S3. S4. RULE 8. Prearrange upgrading, repair and recycling through access ability, labeling, modules, breaking points S3. S4. RULE 9. Promote upgrading, repair, and recycling by using few, simple, recycled, not blended materials and no alloys S6. RULE 10. Use as few joining elements as possible and use screws, adhesives, welding, snap fits, geometric locking, etc. according to the life cycle scenario		●			●	●	

(Continues)

TABLE 4 (Continued)

No.	Type	Type according to classification by Rossi et al. (2016)	Name	Authors	Parameters that correspond to strategies to extend the useful life of products	Type of result: QUANTI-TATIVE	Type of result: QUALITA-TIVE	Reference product: ABSOLUTE COMPARISON	Reference product: RELATIVE COMPARI-SON	Reference product: DOES NOT COMPARE	Segregation of results: SEGREGATED	Segregation of results: NOT SEG-REGATED
27			**Ecodesign PILOT**	Wimmer and Züst (2003) ;http://pilot.ecodesign.at/pilot	S1. Design product for easy handling S4. Design product for optimal adaptability to different users S2. Ensure high reliability of product S2. Ensure high functional quality of the product and minimize the influence of possible variations S4. Design product for possible upgrading S2. Design product for adjustment and adaptation at use stage S3. Design product for easy cleaning and/or minimize susceptibility to soiling S3. Concentrate wear on replaceable components of product S3. Make signs of wear easily visible S3. Indicate servicing intervals for product S3. Ensure maintenance with standard tools S1. Carry out a timeless product design S1. Ensure high appreciation of the product S2. Design product for long service life S2. Carry out a sturdy product design S2. Ensure surfaces are user friendly S2. Ensure corrosion resistance S2. Harmonize service life of individual components S3. Ensure self-explanatory structure or provide for instruction for repair on product S3. Ensure easy access to components for repair and replacement S3. Ensure availability of spare parts S3. Standardize components and/or use identical structural components for different product variants S3. Ensure reworkability of worn components	●				●	●	

(Continues)

TABLE 4 (Continued)

						Type of result		Reference product			Segregation of results	
No.	Type	Type according to classification by Rossi et al. (2016)	Name	Authors	Parameters that correspond to strategies to extend the useful life of products	QUANTITATIVE	QUALITATIVE	ABSOLUTE COMPARISON	RELATIVE COMPARISON	DOES NOT COMPARE	SEGREGATED	NOT SEGREGATED
31			**Fast Five Philips Awareness**	Meinders (1997), Byggeth and Hochschorner (2006)	S2. Durability S3. Reparability S1. Encourage long use	●			●		●	
32	TOOLS		**EcoDesign Checklist Method (ECM)**	Tischner et al. (2000)	S3. Service offers prepared? S2. Robustness, reliability, not susceptible to wear S3. Reparability, maintainability S4. Combinability, adaptability S1. Product readily understandable by users S3. Dirt-repellent, easy to clean	●				●	●	
39			**Circular Design tool**	Moreno et al. (2017)	S2. Ensure reliability (quality) S3. Encourage maintenance (repair/refurbish) S6. Facilitate assembly/disassembly S4. Standardize parts for compatibility (modularity)S3. Ensure availability of spare parts S4. Allow upgradability and flexibility to adapt S1. Customize to wants and needs of each person S2. Enhance durability (avoid built-in obsolescence) S1. Develop attachment/loyalty (experience, meaningful design) S1. Based on long-lasting trends, no ephemeral fashion (timeless aesthetics) S1. Implement poka-yoke principles to make use easier	●				●	●	

(Continues)

TABLE 4 (Continued)

No.	Type	Type according to classification by Rossi et al. (2016)	Name	Authors	Parameters that correspond to strategies to extend the useful life of products	Type of result: QUANTITATIVE	Type of result: QUALITATIVE	Reference product: ABSOLUTE COMPARISON	Reference product: RELATIVE COMPARISON	Reference product: DOES NOT COMPARE	Segregation of results: SEGREGATED	Segregation of results: NOT SEGREGATED
40			**Circularity Potential Indicator (CPI)**	Saidani et al. (2017a, 2017b)	S5. Does the product contain standardized components? S4. Has the product been designed with a modular mindset? S6. Handling and maneuverability of the product (for a single user) S6. Number of different components (regarding the size of the product) S6. Number of joints and connections (regarding the size and number of components) S6. Joints and connection types S6. Joints and connections accessibility S6. Disassembly cost and time (regarding value of the product) S6. Tools required for disassembly S4. Possible upgradability options S3. Possibility of maintenance and repair	●				●	●	
58		**Methods for integrating different existing tools**	**DFE matrix**	Johnson and Gay (1995)	S6. Can the product or component be easily disassembled for upgrade? S3. Are parts readily available for the repair of this product or component? S6. Are snaps, darts, screws of the same head type or other removable fasteners used and are adhesive or welds for joining parts avoided to make it easier to disassemble, repair, reuse or recycle? S3. S4. Is this product designed to be easily repaired and/or upgraded rather than replaced entirely?	●				●	●	

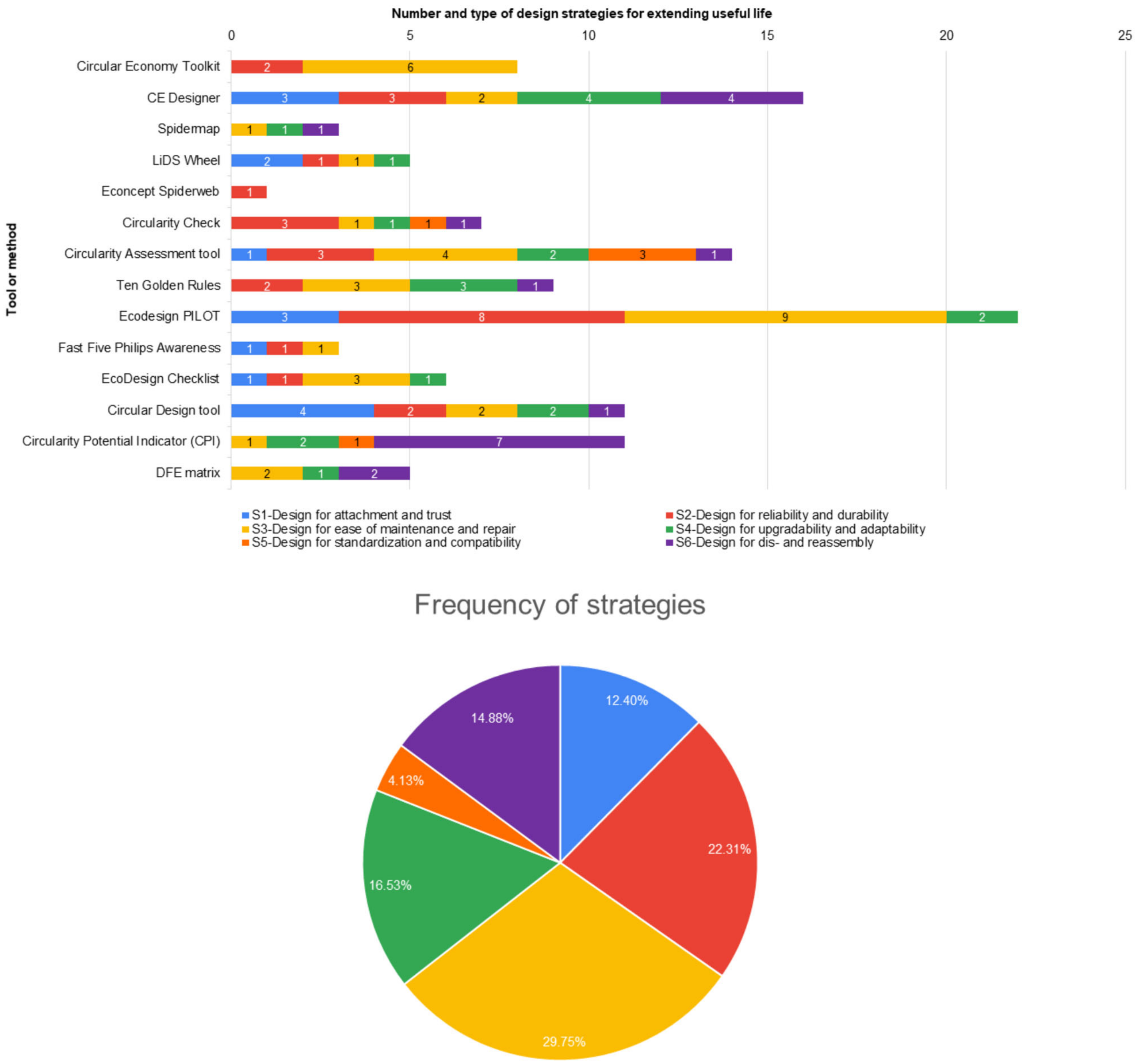

FIGURE 4 Number and type of design strategies for extending the useful life considered by each tool or method from Table 4. The underlying data for this figure can be found in Supporting Information S1.

the useful life or products that contain a list of the parameters of the tool or method that in some way consider useful life extension and the strategies related to each of them. For example, for the CET one parameter is "Product failures are frequent," which corresponds to the design strategy related to extending the useful life coded as S2. Design for reliability and durability.

The results in Table 4 show that 9 of the 14 tools or methods analyzed obtain a quantitative result while the rest (6) obtain a qualitative result. This table also shows that of the 14 tools and methods, 8 assess the results without comparing with a reference product, and 5 make an absolute comparison with a reference product. Only the Fast Five Phillips Awareness method performs a relative comparison.

Finally, the last column of Table 4 indicates whether the results shown by the 14 tools and methods are segregated or not segregated. CE Designer is the only tool that shows the values grouped into two categories, as opposed to the rest, whose results are sorted into different categories, which makes it difficult to carry out an overall assessment of the results.

Figure 4 shows the number of parameters that represent design strategies to lengthen or extend the useful life in each of the 14 tools and methods obtained from Table 4. The Eco-design PILOT tool takes into account the highest number of parameters (22), followed by CE Designer (16), and the Circularity Assessment tool (14). Econcept Spiderweb considers the fewest parameters (one), followed by Fast Five Philips Awareness and Spidermap, which consider three. CE Designer and Circular Design Tool present parameters from five of the six strategies for slowing loops in the classification of Bakker, den Hollander et al. (2014). Only the Circularity Assessment tool presents parameters from the six strategies.

The frequency of the design strategies for lengthening or extending useful life that were found in the 14 tools and methods are analyzed in Figure 4. The useful life extension strategy in which the most parameters were found is "S3. Design for ease of maintenance and repair" with 30% of the total. It is followed by "S2. Design for durability and reliability" with 22.3%, "S4. Design for upgradability and adaptability" with 16.5%, and "S6. Design for dis- and reassembly" with 14.8%. Strategy "S1. Design for attachment and trust" has 12.4% of the parameters identified, and strategy "S5. Design for standardization and compatibility" has the lowest percentage, with only 4.1%.

All the tools present the results segregated, offering the results of each parameter separately, except for the CE Designer tool. This tool groups its 16 parameters into two more general categories than the six strategies indicated by Bakker, den Hollander et al. (2014). These two categories are denominated "Design for Life Extension" and "Design for Durable Products." This aggregation of results can be very convenient for the designer, as it automatically provides two general values related to the extension of the product lifespan that include a total of 16 parameters. Furthermore, it allows an absolute comparison to be carried out with a reference product. As pointed out above, Eco-design PILOT has by far the highest number of parameters that take the extension of the useful life into account, with strategy three being the most frequently considered. Unlike the previous tool, it does not allow comparison with a reference product. The Circular Design Tool presents parameters related to five of the six categories and evaluates them with a quantitative scale without allowing for the comparison of solutions. Circularity Assessment is the only tool that allows all strategies to be considered. In the rest of the tools and methods, one or more strategies to extend useful life are not considered. Eco-concept Spiderweb and CET are the ones that consider the fewest strategies, the former including only S2, while the latter considers just S2 and S3. This second tool allows measurement of the improvement potential of the concept analyzed.

The analysis of the tools shows that most of the strategies found are related to technical product issues, maintenance and repair, durability, and reliability. Such strategies are promoted and considered in the EU Action Plan for the Circular Economy, among others (COM 98, 2020). Adaptability and upgradability and design for assembly and disassembly can be found with a lower percentage. This could be due to the fact that design for assembly and disassembly is also part of higher-level strategies, for example, modularity and reparability (and, consequently, durability) may include requirements for disassembly (Bracquené et al., 2021). Lastly, there are parameters related to attachment and trust. These parameters are more difficult to assess, however, because they are related to user motivation. The lack of strategy S5 in the tools or methods could be due to the fact that it can be assimilated to other strategies such as S2, S4, or S6. This may be because, in the early stages of design, issues such as design for assembly or standardization and compatibility of components are not defined in detail. It is also difficult to relate attachment issues in these phases as the tools themselves do not help with the design approach or strategy to be applied. According to Bakker et al. (2014), functional, emotional, aesthetic, and economic considerations will play an important role in strategic decisions in product design. The emotional attachments that consumers have to their belongings exert an important effect on postponing product replacement (Page, 2014). The latest tools and methods generated in the last few decades help in remanufacturing, design for recycling, and end-of-life (Allwood et al., 2011; Rose, 2001). Most of these tools and guidelines are very function oriented, but they hardly take into account the emotional, aesthetic, and economic consequences of design decisions. Hou et al. (2020) considered that recent evidence reinforces the idea that there are more psychological than functional reasons explaining why consumers choose to replace products. Although attachment is unlikely to be created in purely functional products, their proper functioning can lead to a satisfying experience and attachment can be achieved (Mugge, 2007). Recent studies by Mulet et al. (2022) analyzing attachment factors in purely functional products such as small household appliances indicate that many strategies are not exploited and that attachment could be further increased in these products. The designer's knowledge of practices, methods, and tools would enable effective integration of circularity principles into products (de Pauw et al., 2012). The analysis shows the complexity involved in the application of tools and methods and does not present all the strategies, as shown in Vallet et al. (2013). Authors such as Crul and Diehl (2009, p. 51) have said the following about environmental objectives and strategies: "Remember this is not a precise process but an approximate way of narrowing down the focus for action and reducing the complexity of decision-making." It may be worth considering the development of tools that are more oriented toward product designers.

According to Knight and Jenkins (2009) eco-design techniques may not have been more extensively adopted by companies because such methods are not necessarily generic and immediately applicable, but require some degree of process-specific customization before use, which in turn can be a barrier to adoption. Shahbazi and Jönbrink (2020) analyzed the extent to which a set of circular strategies are integrated in the early stages of product design and development, and adopted by companies. For companies, maintaining their market position against competitors is an essential issue. One of the possible ways to achieve differentiation would be by adopting practices that lead to the development of sustainable products (da Luz et al., 2018), an important aspect that is conducive to sustainability (Moreno et al., 2011). Efforts are being made to develop international standards for different aspects of CE (International Organization for Standardization, 2022), such as the methodology for the eco-design of energy-related products (MEErP) (COWI & VHK, 2011) or the repair score systems (Bracquené et al., 2021; Cordella et al., 2018; Cordella, Alfieri, Clemm, et al., 2021). Sustainability, as considered by Lacasa et al. (2016), is a competitive requirement for companies that are seeking to make responsible decisions about the impacts of their products in the development phase. Therefore, selecting the best tool or method that contributes to the selection of the best product concept that extends its useful life and is therefore more sustainable would help the differentiation of companies in the market.

4 | CONCLUSIONS

This study aims to help designers select the tools or methods that meet two criteria: they can be applied at a conceptual level to compare or assess proposals, and they consider aspects for extending the useful life by recognizing the design strategies they enhance.

The results show that there are very few tools that allow life extension to be measured at a conceptual level, and those that do allow it do not consider a large number of parameters or their application does not allow them to be evaluated or considered easily, although there are approaches to assess the circular economy aspects of products (Cordella et al., 2018; Cordella, Alfieri & Sanfelix, 2021). Furthermore, those parameters referring to personal issues of the user like attachment and trust (Mugge et al., 2005) and specific technical issues that are difficult to apply at a conceptual level should be encouraged. It would also be interesting to assess the tools that consider all the strategies with the same number of parameters with well-written and categorized questions, so as to avoid ambiguity. There are tools that are quite complete, such as CE Designer, which present almost all the strategies and allow evaluation by comparison with another product, as well as offering results that can be evaluated in different categories referring to different design strategies for CE. However, not all the tools offer such complete features. Most of the tools and methods analyzed do not present all the strategies and in some questions their parameters are very general and complex to assess and can be affected by the user experience (Vallet et al., 2013). Salari and Bhuiyan (2015) also considered that the tools and methods do not provide criteria for selecting between different alternatives, they are difficult to learn, to understand and to use, and the information is often vague and general, with no additional information to help the designer. They also consider that they have a weak connection with the product development process and take into account one or two stages of the life cycle. Furthermore, there is a lack of a holistic approach, with qualitative tools such as guidelines and quantitative tools like LCA being used in the initial phases, which require large amounts of data, time, and effort. Neither do they clearly indicate the most appropriate user or promote cross-functional teamwork, as the outcome can be difficult to understand and communicate.

Future work could consist in the elaboration of a more complete tool or method that is easy to apply and with well-defined parameters which would allow designers to assist and quantitatively assess the concepts obtained in all the strategies that refer to life extension. The tools and methods that consider useful life extension could be studied in more detail by analyzing the number and applicability of the parameters, and thus assisting in the creation of new parameters in order to define the parameters correctly. In addition, it would be necessary to foster those strategies that are less considered such as attachment, adaptability, or any of the design strategies that are desired so that the product can be used for longer. In this way, the researcher would be able to assess the application of the different design strategies that refer to the extension of the useful life in the first stages of new product generation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

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