Addressing circular economy through design for X approaches: A systematic literature review

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ARTICLE INFO

ABSTRACT

Guided by a technological revolution, widely discussed paradigms as servitization and Circular Economy (CE) are progressively pushing manufacturers towards delivering increasingly complex solutions. Design plays a strategic role in this sense, either considering products, services or Product-Service Systems (PSSs). Concurrent engineering and, specifically, Design for X (DfX) approaches have been widely associated to products, revealing great potentialities for enhancing service functionalities like supportability and circularity. Again, DfX approaches have been already exploited to systematically support the PSS design process, given their re-known ability to allow a better information sharing between product designers and service managers. However, even if several DfX approaches related with the End of Life (EoL) stage already exist (e.g. Design for recycling, remanufacturing and EoL), they still need to better fit with a circular design perspective. Therefore, the aim of this paper is exploring and understanding how design can contribute towards a CE transition through the adoption of DfX approaches.

Contents

1. Introduction

Considering the high competition of current industrial contexts, manufacturers are asked to deliver products characterized by an increasing complexity (Maeda, 2006; Norman, 2011; Velte and Steinhilper, 2016). Products are supposed to address new circular and digital features to be integrated and systematized with multiple traditional functionalities, often thanks to the introduction of new technologies. From one side, the sustainability (WCED, 1987) and Circular Economy (CE) paradigms (The Ellen MacArthur Foundation, 2015) raised both customers' and providers' awareness about natural resources scarcity. From another side, the servitization paradigm (Vandermerwe and Rada, 1988) supported the advent of a more sustainable economy (Stahel, 1997; Botsman and Rogers, 2010; Bocken et al., 2016), by changing the focus from products to product-related services (Goedkoop et al., 1999). Like evidenced by literature, these two paradigms can be influenced and enabled by technology (Porter and Heppelmann, 2015; Rosa et al., 2019a). In order to pursue this transition, manufacturers have been compelled in changing their business models (Bocken et al., 2014), by detecting and avoiding related hurdles (Brax, 2005; Gebauer et al., 2005; de Jesus Pacheco et al., 2019) and exploring potential benefits (Rosa et al., 2019b). However, methods and tools supporting the systematic integration of product-services under a circular perspective are still under development. Some initial benefits going in this direction have been reached through concurrent engineering (Clark and Fujimoto, 1991; Clausing, 1994). Specifically, Design for X (DfX) guidelines (Gatenby and Foo, 1990; Huang, 1996) are interpreted as a concurrent design of products (and related processes/systems) plus certain abilities in coping with a specific requirement (e.g. features, performance, constraints, etc.). Even if DFX can enhance competitiveness measures, rationalize product/process/resource design decisions and improve operational efficiency in product development (Huang, 1996; Kuo et al., 2001), they are quite old approaches (Gatenby and Foo, 1990). Again, looking at the End of Life (EoL) stage, even if several DfX methods and tools already exist, they still need for a circular perspective (Bakker et al., 2014). Within the Product-Service System (PSS) context DfX have been rarely considered by experts: they have been proposed as a mean to fill in the gap of knowledge of designers about product lifecycle stages, favouring a better information sharing between product designers and service managers (Sassanelli and Pezzotta, 2019). Wrapping up, several DfX research attempts dealing with CE have already been conducted but lacking of an overall and systematized approach. Therefore, the aim of this work is to explore and understand how design can contribute towards a CE transition through the adoption of DfX approaches to deliver suitable product/service/PSS. The paper is organized as follows. Section 2 explains the adopted research methodology. Section 3 presents results coming from the literature review. Section 4 discusses about results. Finally, Section 5 provides some conclusions and future research trends.

2. Materials and methods

In order to better systematize the DfX approaches contributing to a circular design, a systematic literature review has been conducted. The area of investigation didn't focus on the specific context of either product or services or PSSs, looking at the entire extant literature dealing with the circular design through the adoption of the DfX approaches. The keywords "Circular Economy" and its main synonym "end of life" (as suggested by a recent systematic literature review on CE (Sassanelli and Rosa, 2019)) were combined with either "Design for X", "DfX" or "design guideline" and searched without any time/document restriction. Results of these queries are reported in Table 1, confirming that the "end of life" context has been explored more than the "circular economy" one. A total amount of 402 and 339 documents have been found on Scopus® and Science Direct®, respectively. If compared to the more discussed single topics of CE and DfX, these numbers highlight how this combined research context is still under-investigated even if deserving more attention from both researchers' and practitioners' side. Moreover, looking at the same searches performed on titles, abstracts and keywords, results indicate that this research context still represents a niche. After discarding redundancies, a final set of 125 documents was considered for analysis. These documents have been assessed into two ways. A first analysis of titles, abstracts and keywords led to a set of 43 documents. Then, the reading of the entire manuscripts conducted to a final amount of 31 documents. The selection was based on the relevance of documents, taking into account only those contributions proposing DfX approaches and related design guidelines to foster the adoption of the CE paradigm through the delivery of circular solutions. Specifically, authors selected only those documents contributing to a real enhancement of DfX methods and practices under a CE lens, enabling their integration and systematization with traditional product abilities through a concurrent engineering approach.

In particular, Fig. 1 shows the research strategy used in the systematic literature review (Smart et al., 2017; Sassanelli and Rosa, 2019): Table 1 reports the four strings used to carry out the searches on Scopus and Science Direct databases, leading to 741 results. Furthermore, 25 documents were considered through cross-referencing processes and 4 through hand search. Last, 15 more documents were recommended by experts to be added to the list. Applying the criteria, the set of documents found was reduced at the end to 31 selected articles that had been fully analysed. The entire process of selection and examination of the documents was conducted by two authors, carrying it out autonomously to not fall in bias of analysis throughout the review. Finally, their results were compared and made consistent to each other, leading to the research presented in this article.

As shown in next section, all these papers have been categorized by nation of the first author, year, document type, research type (divided in Theoretical Assessment; Analytical Assessment; Case Studies; Surveys; Action Research; Other) and journal. Further-

Table 1
Searches by keywords and documents selection.

Search by keywords	Scopus®		Science Direct®	
	All fields	(Title-Abs-Key)	All fields	(Title-Abs-Key)
"Design guideline" AND "Circular Economy"	33	(5)	10	(1)
"(Design for X" OR "DfX") AND "Circular Economy"	45	(5)	59	(0)
"Design guideline" AND "end of life"	157	(17)	40	(0)
("Design for X" OR "DfX") AND "end of life"	167	(15)	230	(0)
Total	402		339	
Total (without redundancies in the same DB)	75		67	
Total (without redundancies between the two DBs)	125			
Total (after title, abstract and keywords assessment)	43			
Total (after entire manuscript assessment)	31			
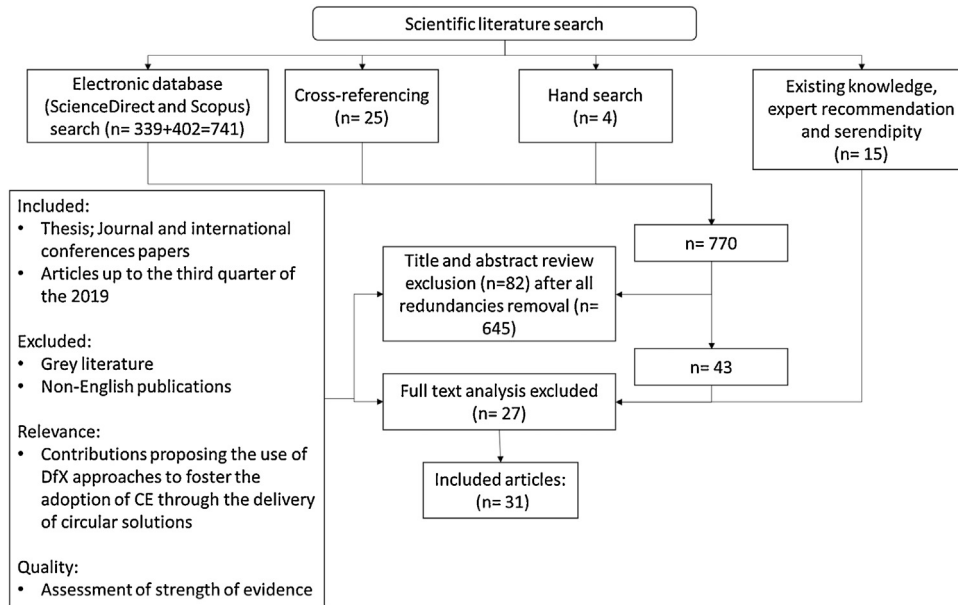
Fig. 1. Research strategy (adapted by (Smart et al. (2017))).
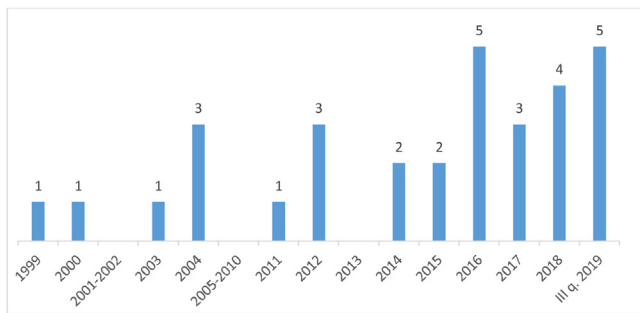
Fig. 2. Historical publication trend by year.

more, in sub-section 3.1 the contributions have been analysed and grouped based on the purpose of using DfX in the design process of circular solutions, the main abilities related to DfX approaches considered to address these purposes and the gaps declared by researchers in each of these categories.

3. Literature review

The trend along the years of the selected 31 articles (Fig. 2) shows a quite steady and weak interest on DfX approaches to foster CE adoption, recording a growth from around 2015 (61.3 % of the contributions are from 2015 onward). This can be justified by the blossom of several directives and regulations indicat-

ing on CE (European Commission, 2014; European Commission, 2015) always more urgent to put right to global issues like resources depletion, consumerism and population growth (The Ellen MacArthur Foundation, 2015).

Concerning the type of contributions (see Fig. 3), 17 were articles published in scientific journals, 10 papers in international conference proceedings and 3 were master/PhD thesis. In line with results coming from other literature reviews on CE (Sassanelli and Pezzotta, 2019), *Journal of Cleaner Production* and *Resources, Conservation and Recycling* are the most recurrent journals (with 50 % of the journal articles considered).

In view of the nationality of authors, European countries provided the majority of contributions selected (71 %), followed by North American countries (16,1%) and Southeast Asian/Chinese countries (12,9%) (Fig. 4).

Assessing the literature, we checked that most of authors gave relevance to the theoretical side, in order to try to define a common ground of theories. 19 times researchers chose to conduct a theoretical assessment of the context without being able to give a complete picture of the DfX needed, mostly due to the multiplicity and heterogeneity of these kind of approaches. Moreover, 6 researches conducted application cases, mainly to validate the methods and tools proposed and 6 were case study to practically explain the proposed approaches or to demonstrate their usefulness. More than half of the contributions (19 of 31) provided only a theoretical view on the relationship between circularity and DfX approaches: only 12 documents proposed application cases and
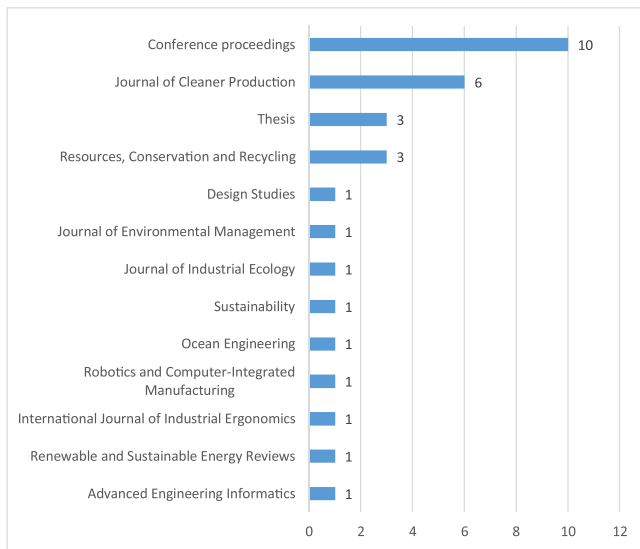
Fig. 3. Type of contributions: journals articles, conference proceedings and thesis.
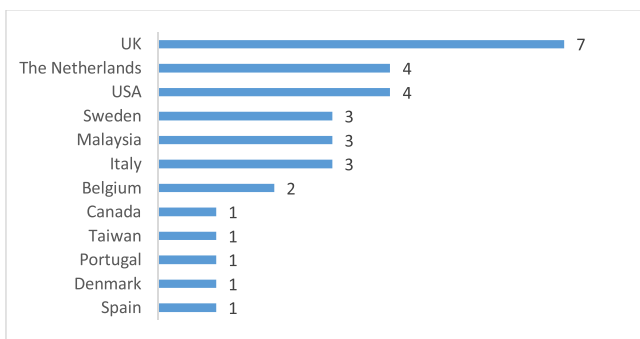
Fig. 4. Publishing countries.

ical analyses (conducted on the specific automotive and maritime industries). Fig. 5 shows the type of products/industries where the proposed guidelines, frameworks and methods have been applied, highlighting that the most relevant ones used to apply circular DfX are Electrical and Electronic Equipment (EEE), photocopiers (and related toner cartridges) and automotive sector. Thus, EEEs (considering photocopiers and toner cartridges industry as one of its sub-group) and End of Life Vehicles (ELVs) industries seem more sensitive to the implementation of DfX to address CE. This can be explained by the fact that they represent the two most important sources of wastes globally, with a not to be neglected percentage of hazardous materials. At the same time, they involve products composed by a large number of different components and materials that remains unprocessed and directed to landfills (Ongondo et al., 2011; Zorpas and Inglezakis, 2012).

3.1. Extant state of the art on DfX approaches supporting the adoption of Circular Economy

In this sub-section, the results of the systematic literature review about the relationship among DfX approaches and CE are reported. The set of 31 documents selected have been analysed (through the SLIP method (which helps to Sort, Label, Integrate and Prioritize key concepts) (Maeda, 2006)) to detect and group:

- the purposes of using DfX approaches to support and foster the adoption of CE,
- for each of these purposes, which ability/ies is/are of major interest,
- the Triple Bottom Line (TBL) perspective considered (since DfX approaches traditionally address economic aspects but can also be oriented to enhance environmental and social ones) and through which abilities each of these perspective is achieved by authors.

All the contributions were focused on understanding how design can contribute to the circular transition through the adoption of DfX approaches. The majority (15) was aimed at improving the design process under a circular perspective, some of them (8) were oriented to focus the design process attention on circular metrics and evaluations, few of them had the objective to support the

case studies to demonstrate the value of the proposed researches from a practical perspective. These 12 documents proposed in total 59 cases: 47 cases were coming from master and PhD theses, 10 from action research and case studies papers and 2 from theoret-
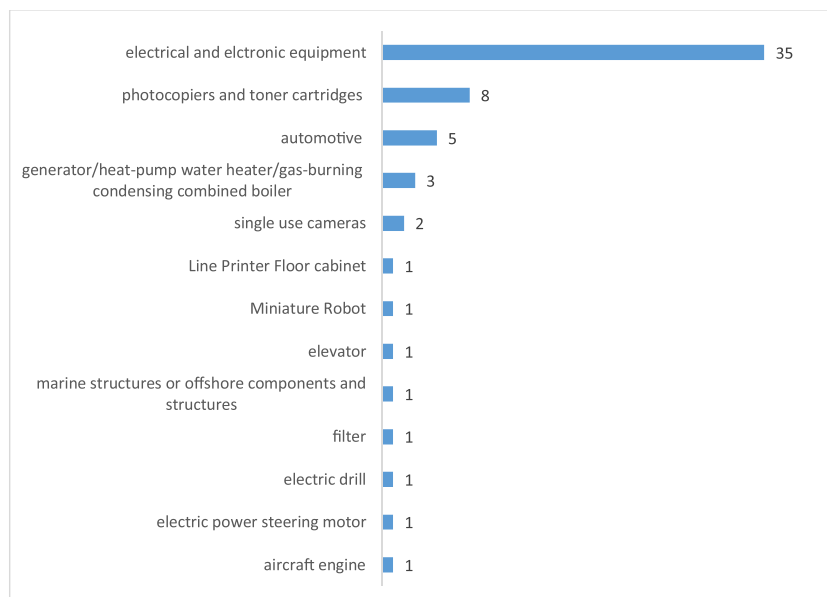
Fig. 5. Industries.

Table 2
DfX purposes fostering circularity adoption.

|	DfX purpose				
	Circular design improvement	Circular design metrics and evaluation	Circular design decision-support	Design driving circular transition	Circular design knowledge management
Total	15	8	3	3	2
	(Bakker et al. (2014)); (Ceschin and Gaziulusoy (2016)); (Go et al. (2015)); (Moreno et al. (2016)); (Pigosso and McAloone (2017)); (van der Laan and Aurisicchio (2019)); (Vanegas et al. (2018)); (Wahab et al. (2018)); (Sundin (2004)); (Hultgren (2012)); (Allwood et al. (2011)); (Rose (2000)); (Peeters et al. (2012)); (Arnette et al. (2014)) (Favi et al. (2019))	(Bovea and Pérez-Belis (2004)); (Mendoza et al. (2017)); (Rocha et al. (2019)); (Rossi et al. (2016)); (Van den Berg and Bakker (2015)); (Shu and Flowers (1999)); (Desai and Mital (2003)); (Mayyas et al. (2012))	(Gould et al. (2017)); (Kuo et al. (2019)); (Pozo Arcos et al. (2018))	De Los Rios and Charnley (2017); (Bhamra (2004)); (Rahito et al. (2019))	(Favi et al. (2016)); (Toxopeus et al. (2018))

decision-making along circular design process (3), the transition through design towards circularity (3) and the knowledge management process throughout circular design (2). Table 2 reports some details about the final set of 31 papers.

All the detected purposes played by DfX approaches under a circular perspective (see Fig. 6 below), have been analysed in terms of mean proposed/used (method, tool, framework, guidelines, recommendations, literature review, model) to address circularity, main abilities to be addressed (and related secondary abilities and features), TBL perspective considered to address circularity and research gaps to be filled.

Indeed, each document has been analysed under a twofold perspective with the DfX lenses to understand how these approaches have been used to address CE so far. The documents selected have been analysed not only to understand for which purposes DfX approaches have contributed to CE adoption (leading to the classification presented in Fig. 6 above) but also to define which DfX abilities have been considered to address these different purposes. The DfX Ability is based on the "function" concept explained by (Mital et al., 2008), p. 251). They define a function as the ability of a product "*to do something (performance), safely, reliably, in a usable manner, in a high-quality manner, with concern for manufacturability and environment friendliness*". Abilities are hence those principles through which the function can be explicated and explained and represents what precisely the DfX approach addresses (Huang, 1996; Sassanelli and Pezzotta, 2019). Given the huge amount of approaches in extant literature, abilities reported in the set of documents analysed were first grouped in main and secondary abilities oriented to achieve circularity. Finally, only the main abilities have been considered and grouped in this analysis (using the SLIP method (Maeda, 2006)) to set the categories of circular DfX abilities. These abilities are clustered in 5 main classes:

1 Supply Chain (SC): it takes account of the role of the SC during the design phase in terms of coordination, collaboration and integration to deliver circular or/and sustainable value to the customer (Lee and Billington, 1992), covering the whole spectrum of value creation for both biological and technological cycles (Charnley et al., 2011). It is declined in approaches as Design for:
   - Design for: SC; Circular/Sustainable SC; System Change.
2 Resource/energy efficiency: it considers the ontological characteristic of the CE paradigm of minimizing the negative effects

of finite resources consumption, by focusing on intelligent design of materials, products and systems (The Ellen MacArthur Foundation, 2015) to minimise emissions, resource use, pollution and waste, and maximise the resource efficiency of material assets (Stahel and Reday-Mulvey, 1981; Pearce and Turner, 1991). It gathers approaches as:
   - Design for Resource efficiency and conservation (DfREf&C).
3 Reliability: it includes approaches aimed at improving either the inner capacity of the product to address reliability and safety throughout the entire lifecycle or those ones oriented at slowing and extending the lifecycle to prolong their use phase (e.g. through maintenance). This category is declined in approaches as:
   - Design for Slowing Lifecycle (DfSLC); Design for Long life Use of Products (DfLLUoP); Design for Maintenance (DfMa); Design for Product-life extension (DfPLExt),
   - Design for Reliability (DfRel) and Design for Safety (DfSa).
4 Multiple Life Cycle (MLC): this category considers all those approaches aimed at enabling the MLC of resources. Several circles are enabled closing the loop and addressing the sustainable use of resources. Both biological and technical cycles are considered in these virtuous approaches. Six main sub-categories have been detected, mainly based on either the different strategy adopted to close the loop (e.g. disassembly or remanufacturing or recycling) or the inner products properties able to foster the adoption of these strategies (e.g. modularity or ease of access). They consist in approaches as:
   - Design for Multiple Life Cycles (DfMLC); future proof design; technical cycle; biological cycle; closed-loop PSS; ease of cleaning/storage/access,
   - Design for Disassembly and Reassembly (DfD&Rea),
   - Design for Remanufacturing (DfRem); Design for Remake (DfRema); Design for Recovery (DfReco),
   - Design for Recycling (DfRecy),
   - Design for End-of-Life (DfEoL),
   - Design for: Adaptability; Standardization; Compatibility; Modularity; Upgradability.
5 Sustainability: this category is funded on the tangled relation between sustainability and CE (Merli et al., 2018). Here converge all the approaches addressing sustainability, declined throughout the TBL (WCED, 1987) with its threefold perspective (economic, environmental, social).
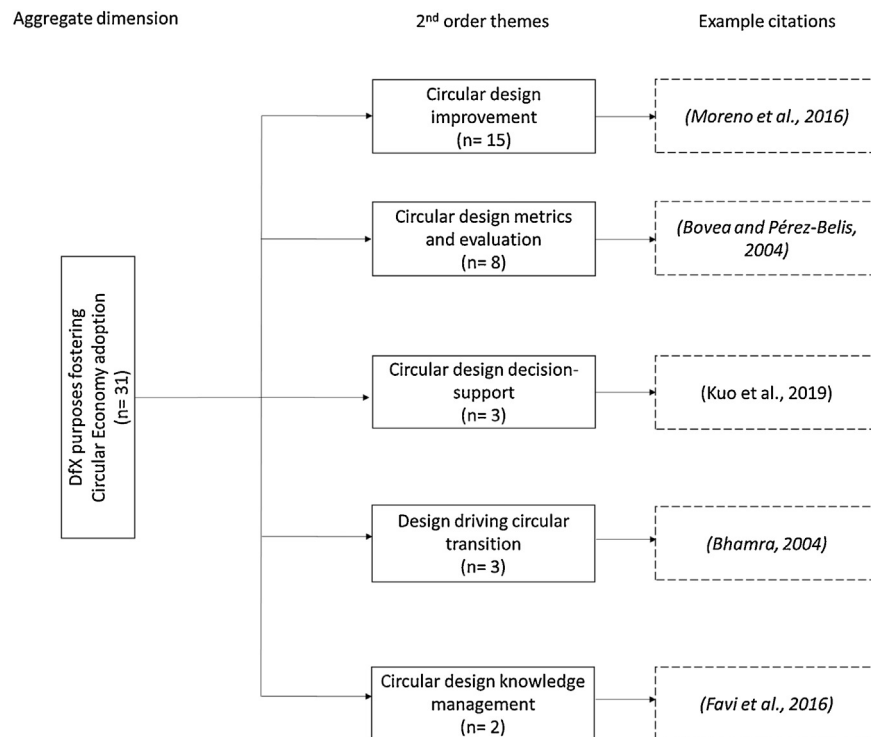
Aggregate dimension　　　　　　　　　　　2nd order themes　　　　　　　　Example citations

Fig. 6. Scheme of DfX purposes fostering Circular Economy adoption.

- Design for Sustainability (DfSu),
- Design for Environment (DfE),
- Design for Social Responsibility (DfSR).

Moreover, authors consider relevant to provide a brief overview also of the secondary approaches, reporting some examples. From one side, on the product level, emotionally durable design, design for product attachment, green and eco-design, design for sustainable behaviour, cradle-to-cradle design and biomimicry design. Instead, from a PSS perspective, PSS design for eco-efficiency, PSS design for sustainability and PSS design for the Bottom of the Pyramid (BoP), design for social innovation, systemic design, design for systems innovations and transitions. In addition, design for logistics, design for procurement, design for reverse logistic contributed to enrich the SC category. Finally, other approaches were aimed mainly at strengthening the sustainable and environmental aspect: radical innovation for sustainability, design for cascaded use, design for energy performance, design for dematerialization, design for responsible user-behaviour, design for flexibility, design for mass customization, design for chronic risk reduction, design for energy conservation, design for material conservation, design for waste minimization & recovery.

Furthermore, it is worth to analyse the twofold DfX-CE research context through the type of researches conducted and the contributions proposed by researchers (Table 3). In general, most researches conducted were mostly theoretical. Indeed, just one of the five DfX purpose categories, *Circular Design KM*, is characterized only by practical contributions. In this case only methods and tools were proposed to foster an easier sharing and utilization of design knowledge. Instead, in the case of *Circular Design Improvement* category, the majority of contributions were theoretical, sometimes gathering as a result guidelines provided in literature and sometime also proposing new methods to define values as the product lifespan and disassembly time or to improve the product characteristics for easing recycling and remanufacturing. The *Circular Design Metrics and Evaluations* category mainly presents frameworks and models

to ensure a better implementation of CE requirements or to quantify the cost of joints throughout the remanufacturing processes. In the *Circular Design Decision-Support* category, literature reviews and a case study concur to provide not only a framework and a method selecting the most suitable sustainable design strategies and providing hints on how to implement them but also recovery guidelines supporting the decision-support process. Finally, in the *Design Driving Circular Transition* contributions, only theoretical assessments were conducted, providing literature reviews concerning the research context.

In the following sub-sections, the set of 31 contributions selected are described based on the aggregate dimension of analysis, named DfX purposes fostering circular adoption (shown in Fig. 6).

3.1.1. Circular design improvement

As reported in Table 2, the most common purpose justifying the adoption of DfX to foster and address circularity is the improvement of the design of products/service/systems from a circular perspective (Rose, 2000; Sundin, 2004; Allwood et al., 2011; Hultgren, 2012; Peeters and Dewulf, 2012; Arnette et al., 2014; Bakker et al., 2014; Go et al., 2015; Ceschin and Gaziulusoy, 2016; Moreno et al., 2016; Pigosso and McAloone, 2017; Vanegas et al., 2018; Wahab et al., 2018; van der Laan and Aurisicchio, 2019).

(Bakker et al. (2014)) explored how product design can more proactively address product life extension (through longer product life, refurbishment and remanufacturing) and product recycling. Based on the Waste Framework Directive, they selected three main strategies for product life extension and recycling: prevention, reuse and recycling. In order to address one of these three strategies, it is important to realize how to define product lifespan from both an environmental and economic perspective. The challenge is to determine when to apply which product life extension strategy. For this reason, they proposed a methodology to determine the optimal product lifespan, applied to two case studies on a domestic refrigerator and a laptop.

Table 3
Type of researches and contributions proposed.

DfX purposes fostering circular adoption	Authors	Research type			Mean			
		Theoretical assessment	Case studies	Action research	Method/tool	Framework /model	Guidelines	Literature review
Circular Design Improvement	(Bakker et al. (2014))		x		x			
	(Ceschin and Gaziulusoy (2016))	x						x
	(Go et al. (2015))	x					x	x
	(Moreno et al. (2016))	x				x	x	
	(Pigosso and McAloone (2017))	x						x
	(van der Laan and Aurisicchio (2019))	x					x	
	(Vanegas et al. (2018))		x		x			
	(Favi et al. (2019))		x		x			
	(Wahab et al. (2018))	x						x
	(Sundin (2004))			x	x			
	(Hultgren (2012))			x			x	
	(Allwood et al. (2011))	x					x	
	(Rose (2000))	x			x			
	(Peeters et al. (2012))	x					x	
	(Arnette et al. (2014))	x						x
Total per DfX purpose		**10**	**3**	**2**	**4**	**1**	**6**	**5**
Circular Design Metrics and Evaluation	(Bovea and Pérez-Belis (2004))		x		x			
	(Mendoza et al. (2017))		x			x		
	(Rocha et al. (2019))	x				x		
	(Rossi et al. (2016))	x					x	x
	(Van den Berg and Bakker (2015))	x				x		
	(Shu and Flowers (1999))			x		x		
	(Desai and Mital (2003))			x	x			
	(Mayyas et al. (2012))	x						x
Total per DfX purpose		**4**	**2**	**2**	**2**	**4**	**1**	**2**
Circular Design Decision-Support	(Gould et al. (2017))	x			x			
	(Kuo et al. (2019))		x			x		
	(Pozo Arcos et al. (2018))	x						x
Total per DfX purpose		**2**	**1**	**0**	**1**	**1**	**0**	**1**
Design Driving Circular Transition	De Los Rios and Charnley (2017)	x						x
	(Bhamra (2004))	x						x
	(Rahito et al. (2019))	x						x
Total per DfX purpose		**3**	**0**	**0**	**0**	**0**	**0**	**3**
Circular Design KM	(Favi et al. (2016))			x	x			
	(Toxopeus et al. (2018))			x	x			
Total per DfX purpose		**0**	**0**	**2**	**2**	**0**	**0**	**0**
Total of all DfX purposes		**19**	**6**	**6**	**10**	**6**	**7**	**11**

(Ceschin and Gaziulusoy (2016)) explored how DfSu approach evolved, grouping the design approaches proposed in the extant literature in four innovation levels: Product, PSS, Spatial-Social and Socio-Technical System. To this aim, they assessed DfX guidelines and toolkits supporting sustainable attitudes. At product level, emotionally durable design and Design for product attachment were defined complementary to the more basic green and eco-design approaches. Moreover, Design for Sustainable Behaviour addresses the product impact throughout its whole life cycle, while cradle-to-cradle design and biomimicry design were considered to contribute to the EoL. In addition, Design for the Base of the Pyramid (BoP) was supposed to support social issues, mostly through PSS-based BMs adoption (Emili et al., 2016). In the PSS context, researchers considered environmental and economic approaches (as PSS design for eco-efficiency) and included also the social aspects (through PSS DfSu and PSS DfBoP). The spatial-social level unveiled a need for technological innovations to be complemented by social innovations through approaches as design for social innovation. In this dimension also systemic design was introduced, focusing on the concept of waste (materials and energy) flows, designed to become inputs to other processes. Lastly, at the socio-technical system innovation level, Design for Systems Innovations and Transitions was considered as the strategic approach to embody the PSS design.

As well, (Moreno et al. (2016)) proposed a conceptual framework for CE design strategies starting from an analysis of the extant literature on DfSu combined with CBMs. Based on the DfX approaches taxonomy by (De los Rios and Charnley (2017)), they detected five main circular design strategies:

1 Design for circular supplies
2 Design for resource conservation
3 DfMLC
4 DfLLUoP
5 DfSysC

After reviewing DfX approaches and proposing their adoption as a fundamental mean to pursue the transition towards circular design, they proposed 10 recommendations to be considered when designing for a CE.

Instead, (Go et al. (2015)) analysed and grouped the design guidelines coming from those DfX approaches concurring to the

definition of DfMLC. They defined DfMLC as a mixture of eco-design strategies (DfE, DfRem, Design for Upgradability, DfA, DfDis, Design for Modularity, DfMa and DfRel) that they mapped with MLC options (reuse/remanufacturing/recycling) processes (core collection, inspection, disassembly, cleaning & storage, remediation, reassembly, testing). They reported the main guidelines per each of these approaches arguing that their concurrent adoption can ground the circular design of future products.

(Pigosso and McAloone (2017)), through a systematic literature review, identified "design methods and tools", "Product, service and system design" and "Design for X/Design to X" as the three main design topics in the CE context. Concerning DfX, they recognized the key role of such approaches in circular design (impacting on different aspects as cost, aesthetics and performance), also revealing the role of digital technologies, IoT and big data as enablers for CE. Moreover, also in this case PSS seemed to be a promising approach for CE, to be supported by suitable design guidelines and sustainability evaluation methods.

Since extant researches focused on developing PSSs that narrow and slow resource flows (Bocken et al., 2016; Blomsma et al., 2018) rather than closing resource loops, (van der Laan and Aurisicchio (2019)) provided 10 guidelines for the design of closed-loop PSSs, grouped in 4 dimensions: state lifetime; govern lifetime; intercept obsoletes; transition obsoletes.

Based on the need raised in the EU action plan for the CE (European Commission, 2015) to develop standards on material efficiency to set durability, reparability and recyclability requirements, (Vanegas et al. (2018)) proposed a method, "eDiM" (ease of Disassembly Metric), aimed at computing the disassembly time to measure ease of disassembly, compare alternative product designs and measure recoverability. Being time a valid metric for disassembly modelling, they categorized disassembly tasks in six categories (tool change, identifying connectors, manipulation, positioning, disconnection, removing) to better understand which ones are the most time-consuming and how they could be improved. (Favi et al. (2019)) proposed a DfD method and tool, the LeanDfD, to aid designers and engineers in the implementation of re-design actions for improving product de-manufacturability and EoL performances. The methodology is composed of four main steps (target components, precedencies, liaisons and properties, disassembly times &costs). Quantitatively assessing the disassemblability and recyclability of mechatronic products through suitable indicators, the LeanDfD package can:

- assess the design decisions
- store and classify disassembly data (standard times and corrective factors of each disassembly liaison and operation) to create valuable knowledge, useful to:
  - conduct time-based analysis and improve the disassemblability performance of target components
  - estimate the quantities of materials that could be potentially recycled at the product EoL.

(Wahab et al. (2018)) performed a review of remanufacturing to extend life cycle of marine structures, presenting DfRem as the enabler for life cycle reliability and safety. Indeed, demanding a warranty to products' original specification and requiring formal certifications to ensure functionality and safety performances, remanufacturing can be considered the best EoL recovery strategy. In this context, they discussed how the incorporation of DfRem contributes to enhance reliability and safety for life cycle extension in each of the different stages of embodiment design. In architecture design, architectures modularity ensures reliability and safety during the use phase, minimizing design complexity and facilitating accessibility, part replacement and maintenance. In configuration design, durable materials, reliable and standard parts are consid-

ered to support and ease disassembly and reassembly, inspection and cleaning, repair and restoration. In parametric design, DfD, Design for Easy Cleaning, Design for Restoration, Design for ease of inspection, were selected to improve the remanufacturing performances.

(Sundin (2004)) focused on DfE and DfRem, not neglecting conflicts between different DfX approaches. He introduced the RemPro-matrix, identifying the product properties to be considered when a product has to be remanufactured (wear resistance, ease of: identification, verification, access, handling, separation, securing, alignment, stacking) and showing their relationship with the steps composing the remanufacturing process (inspection, cleaning, disassembly, storage, repair, reassembly, testing). Finally, in Ref. (Sundin et al., 2009), in light of the previous research they underlined how to adapt product to PSS with a lifecycle perspective in the design phase.

(Hultgren (2012)) created guidelines and design strategies on recyclability to support engineers in designing products that are easier to recycle. She obtained 4 main guidelines (mainly dealing with: hazardous materials and components; their ease of access and removal; recyclable materials; connections enabling liberation) declined in a set of 14 design strategies. Indeed, these guidelines can be exploded in several design strategies containing more specific practical DfRecy advices. She involved different concepts (such as DfE and DfSu, DfD and DfReco) in general guidelines to improve the environmental performance of products.

(Allwood et al. (2011)) discussed four main strategies for reducing material demand through material efficiency (longer-lasting products; modularization and remanufacturing; component reuse; designing products with less material) and reported design guidelines supporting remanufacturing, based on (Sundin and Bras (2005)) work.

(Rose (2000)) proposed a design tool, EoL Design Advisor (ELDA), using simple product characteristics to make EoL strategy decisions based on designers' and product managers' recycling experiences. Moreover, she defined six EoL strategies (reuse, service, remanufacture, recycling with assembly, recycling without disassembly, disposal) to map product characteristics with the possible EoL treatment of the product. She detected six final technical product characteristics (wear-out life, technology cycle, level of integration, number of parts, design cycle, reason for redesign) because of their strong influence over the product EoL strategy. In (Rose and Stevels, 2001), the Environmental Value Chain Analysis was combined with ELDA. By analysing the value chains of existing product EoL systems, they were able to identify the appropriate EoL strategy and enhance some of them as take-back and recycling systems.

(Peeters et al. (2012)) gathered general design guidelines for different demanufacturing strategies, highlighting that guidelines related to disassembly are often clashing with those aimed at dismantling, smashing or shredding. However, also in this case it was recognized the importance of fasteners for products to be repaired, reconditioned or remanufactured in view of the disassembly process (either manual or automated or active). They concluded categorizing three different types of products to be involved in the remanufacturing process:

- PSS-based products (in which the provider is impelled to implement design improvement to ease the demanufacturing process)
- electronic products (in which non- or semi-destructive demanufacturing processes, through active fasteners, strongly facilitate multiple lifecycles of the products)
- products to be not repaired, remanufactured or refurbished (in which the value of design to support disassembly is minor, and large form locking fasteners and loose fits can be used to enact destructive demanufacturing process)

On the same line, (Arnette et al. (2014)) started from the consideration that for products sold within a PSS, in which the provider retains the product property rights, there are direct economic stimuli for manufacturers or retailers for implementing design improvements which facilitate demanufacturing processes. Thus, they grouped DfX approaches in four categories under the DfSu umbrella. Under the economy dimension they considered approaches as: SC, Logistics, Manufacturing and Assembly, Flexibility (Mass Customization, Modularity), Quality and Reliability, Procurement, Supportability (Maintainability, Serviceability). The ecology dimension groups approach as Design for: Environment, Chronic Risk Reduction, Energy Conservation, Material Conservation, Waste Minimization & Recovery, Remanufacturing, Reuse & Recycling. The twofold dimension Economy and Ecology was composed by DfD and Design for Reverse Logistic. Last, under an Equity perspective, DfSR was considered. The three dimensions of sustainability seem to be interrelated through their three main approaches detected by the authors: DfSC (economic), DfE (environmental) and DfSR (social). In detail, the economic dimension collects all the traditional DfX approaches under the concept of DfSC, focusing on the sourcing, production and distribution processes. At this purpose, since the decision of the DfX criteria to be applied are linked to the product lifecycle phases to be strengthened, DfX considered in the taxonomy were also mapped based on five main lifecycle sub-phases (sourcing, production, distribution, use, EoL) and combined with the business strategy to be adopted (low-cost leadership, product differentiation).

Table 4 shows that, when the purpose of DfX approaches is *Circular design improvement*, researchers involved all the five macro-categories of DfX detected but focusing on MLC and sustainability categories, mostly adopting DfRem/Rema/Reco, DfE and DfD&Rea. In general terms, the TBL perspective was always focused on environmental aspects, sometimes related to economic aspects and few times with the social side.

3.1.2. Circular design metrics and evaluation

(Bovea and Pérez-Belis (2004)) re-organized from a CE perspective 46 design guidelines coming from the eco-design framework (Bhamra, 2004) and several DfX approaches (DfE (Gertsakis et al., 2001), DfDis (Dowie and Simon, 1994), DfReco (Hultgren, 2012), DfRem (Sundin, 2004)). In addition, other new design guidelines were proposed and gathered in five main circular design groups: extending life span, disassembling, product reuse, components reuse, and material recycling. After providing a set of practical design guidelines, they also presented a methodology that allows the analysis of how an existing product design meets the design guidelines required from the circular economy perspective. The methodology was applied on twelve case studies, defining two main criteria to define circularity degree (margin of improvement and relevance).

(Mendoza et al. (2017)) presented a framework, Back casting and Eco-design for the Circular Economy (BECE), to ensure that businesses can implement CE requirements more readily. They categorized product design and business model strategies in two main actions, slowing (i.e. design for long-life products, DfPLExt (DfMa and repair, upgradability and adaptability, standardization and compatibility, and DfD&Rea), and closing resource loops (i.e. design for a technological cycle, design for a biological cycle, and DfD&Rea).

(Rocha et al. (2019)) proposed an analytical framework for DfSu models, distinguishing the strategic, tactical and operational design activities and linking each dimension with design management and corporate social responsibility literatures. The corporate sustainability management and design management were suitable to build a framework for analysis of the existing selected models, and

allowed to explore DfSu use into practice, at strategic, tactical and operational levels.

(Rossi et al. (2016)) conducted a review of eco-design methods and tools to enable an effective implementation of CE in industrial companies. Among the others, they suggested checklist and guidelines approach to quickly evaluate the product's environmental profile and to make suggestions to the design team to solve problems during the first design phases. DfX approaches, usually used by the design team to manage product-specific solutions, are suggested to be strongly considered in the field of eco-design: DfD, DfRema, DfReco, DfRecy and the Design for Energy Efficiency approaches.

(Van den Berg and Bakker (2015)) provided a CE framework from a product design perspective. In order to extend the design for CE research context by already explored fields as disassembly, remanufacturing and recycling, they performed a review of the extant CE terminology and defined five most design-relevant topics: future proof design, DfD, DfMa, remake and DfRecy. Two main streams were detected. On one side, futureproof is aimed at making products last longer (involving principles as performance, reliability, durability) or at prolonging their use (through upgradability, adaptability, timeless design, road-mapping, anticipating legislation). On the other side, disassembly can be considered alone (acting on connections or product architecture through principles as ease of access, quick disconnections, simple architectures, clarity of disassembly, etc.) or combined. When combined, it can be addressed either with only non-destructive practices, maintenance for reuse of products (based on ease of cleaning, ease of repair/upgrade, onsite repairability and upgradability) and remake of components (grounded on modularity, reliability assessment and reverse logistics), or destructive/non-destructive practices, i.e. recycle (to reuse materials, electronics or connections through a fast and easy detection, modularity, use of non-fixed connections).

(Shu and Flowers (1999)) investigated both literature and practice to explore DfRem: in particular, its conflict with other DfX approaches was assessed (focusing on DfMA, DfMa, and scrap-material recycling), reporting examples of design tips in each of them. They detected six processes (disassembly, sorting, cleaning, refurbishment, reassembly and testing) to ease remanufacturing, considering fasteners and joints design as strategic in all them. Finally, they proposed a framework (to quantify in all these processes the cost of joints, better describing repair activities executed throughout remanufacture). (Desai and Mital (2003)) proposed a methodology that assigns time-based numeric indices to several design factors (e.g. effort of manual force for disassembly, precision required for tool placement, weight, size, disassembled components material and shape, hand tools, etc), so far considered only separately in literature. Their calculation allows the detection of disassembly anomalies (addressing disassembly sequence planning or economic analysis), design modifications and finally also disassembly improvement. (Mayyas et al. (2012)) conducted a review of the extant contributions on vehicles' life cycle, disposal and EoL analyses, also studying the sustainability metrics used to measure the environmental impact. The review categorized under a TBL perspective the literature into four main research areas (the life cycle assessment approach, the EoL perspective, the DfX, the lightweight engineering and material selection studies). Concerning DfX area, based on a previous study by (Jawahir et al. (2007)), they declined DfSu into 4 main groups: DfMA, DfRecy/DfEoL (comprising DfD, DfRem, DfRecy, Design for reusability), Design for Minimize Material Usage (durability, energy efficiency).

Table 5 illustrates that to support the category *Circular design metrics and evaluation* researchers did not focus on SC abilities. Instead, they concentrated their efforts on both enabling MLC (mainly through DfRem/Rema/Reco and DfD) and addressing sustainability (mostly through DfE). Indeed, MLC and sustainability

Table 4
Circular design improvement category.

Authors	Objective	Main Abilities												Other	TBL		
		SC	Res/En Eff	Rel		Multiple Life Cycle (MLC)				Sustainability					Eco	Env	Soc
		C/S SC; SysC	REf&C	SLC; LLUoP Ma; PLExt	PRel & Sa	MLC; FPD; D&Rea TecC; BioC; CLPSS; EofC/S/A	Rem; Rema; Reco	Recy	EoL	Ad; St; Com; Mo; Upg	Su	E	SR				
(Bakker et al. (2014))	To determine the optimal product lifespan.		x	x			x	x	x						x	x	
(Ceschin and Gaziulusoy (2016))	To define DfSu.										x				x	x	x
(Go et al. (2015))	To detect DfX approaches concurring to the definition of DfMLC.					x										x	
(Moreno et al. (2016))	To guide the design process under a circular economy perspective.	x	x	x		x										x	
(Pigosso and McAloone (2017))	To define how design can contribute to CE.					x								Properties Cost; Aesthetics; Performance	x	x	
(van der Laan and Aurisicchio (2019))	To provide guidelines for the Design of closed-loop PSSs.					x									x	x	
(Vanegas et al. (2018))	To compute the disassembly time.						x								x	x	
(Favi et al. (2019))	To support the implementation of re-design actions for improving product de-manufacturability and EoL						x	x							x	x	
(Wahab et al. (2018))	To discuss the link among remanufacturing, reliability and safety for life cycle extension.				x		x								x	x	
(Sundin (2004))	To identify the product properties to be considered when a product has to be remanufactured						x					x				x	
(Hultgren (2012))	To support engineers in designing products that are easier to recycle.						x	x			x	x				x	

Table 4 (*Continued*)

Authors	Objective	SC	Res/En Eff	Rel		Multiple Life Cycle (MLC)						Sustainability				Other	Eco	Env	Soc
		C/S SC; SysC	REf&C	SLC; LLUoP; Ma; PLExt	Rel & Sa	MLC; FPD; D&Rea TecC; BioC; CLPSS; EofC/S/A	Rem; Rema; Reco	Recy	EoL			Ad; St; Com; Mo; Upg	Su	E	SR				
(Allwood et al. (2011))	To support DfRem.						x											x	
(Rose (2000))	To use simple product characteristics to make EoL strategy decisions based on recycling experiences with designers and product managers.												x					x	
(Peeters et al. (2012))	To gather general design guidelines for different demanufacturing strategies.					x												x	
(Arnette et al. (2014))	To propose a taxonomy of DfX approaches in four categories under the DfSu umbrella.	x										x	x	x			x	x	x
Total per ability		**2**	**2**	**2**	**1**	**4**	**4**	**4**	**3**	**1**	**0**	**3**	**4**	**1**		**1**	**8**	**15**	**2**
Total per aggregate abilities		**2**	**2**	**3**		**16**						**8**				**1**			

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SC = Supply Chain; C/S SC = Circular/Sustainable SC; SysC = System Change; Res/En Eff = Resource/Energy Efficiency; Ref&C = Resource Efficiency and Conservation; Rel = Reliability; SLC = Slowing Life Cycle; LLUoP = Long Life Use of Products; Ma = Maintenance; PLExt = Product Life Extension; Rel & Sa = Reliability and Safety; MLC = Multiple Life Cycle; FPD = Future Proof Design; TecC = Technical Cycle; BioC = Biological Cycle; CLPSS = Closed-loop PSS; EofC/S/A = Ease of Cleaning/Storage/Access; D&Rea = Disassembly and Reassembly; Rem = Remanufacturing; Rema = Remake; Reco = Recovery; Recy = Recycling; EoL = End of Life; Ad = Adaptability; St = Standardization ; Com = Compatibility; Mo = Modularity; Upg = Upgradability; Su = Sustainability; E = Environment; SR = Social Responisibility; TBL = Triple Bottom Line; Eco = Economic; Env = Environmental; Soc = Social.

Table 5
Circular design metrics and evaluation category.

Authors	Objective	Main Abilities												Other	TBL		
		SC	Res/en Eff	Rel		Multiple Life Cycle (MLC)				Sustainability					Eco	Env	Soc
		C/S SC; SysC	REf&C	SLC; LLUoP Maint; PLExt	Rel & Sa	MLC; FPD; D&Rea TecC; BioC; CLPSS; EofC/S/A	Rem; Rema; Reco	Recy	EoL	Ad; St; Com; Mo; Upg	Su	E	SR				
(Bovea and Pérez-Belis (2004))	to assess if an existing product meets the design guidelines from a CE perspective + guidelines.					x	x	x	x	x						x	
(Mendoza et al. (2017))	to ensure that businesses can implement CE requirements more readily.			x		x	x			x						x	
(Rocha et al. (2019))	to analyze DfSu models.										x				x	x	x
(Rossi et al. (2016))	to suggest checklist and guidelines approach to quickly evaluate the product's environmental profile.		x			x	x									x	
(Van den Berg and Bakker (2015))	to define five most design-relevant topics.			x		x	x	x								x	
(Shu and Flowers (1999))	to quantify in all the six remanufacturing sub-processes (disassembly, sorting, cleaning, refurbishment, reassembly and testing) the cost of joints.						x								x		
(Desai and Mital (2003))	to assign time-based numeric indices to several design factors.						x								x		
(Mayyas et al. (2012))	to measure the environmental impact.										x				x	x	x
Total per ability		**0**	**1**	**2**	**0**	**2**	**5**	**4**	**1**	**1**	**1**	**2**	**1**	**0**	**0**	**4**	**6**	**2**
Total per aggregate abilities		**0**	**1**	**2**		**14**						**3**			**0**	**4**	**6**	**2**

SC = Supply Chain; C/S SC = Circular/Sustainable SC; SysC = System Change; Res/En Eff = Resource/Energy Efficiency; Ref&C = Resource Efficiency and Conservation; Rel = Reliability; SLC = Slowing Life Cycle; LLUoP = Long Life Use of Products; Ma = Maintenance; PLExt = Product Life Extension; Rel & Sa = Reliability and Safety; MLC = Multiple Life Cycle; FPD = Future Proof Design; TecC = Technical Cycle; BioC = Biological Cycle; CLPSS = Closed-loop PSS; EofC/S/A = Ease of Cleaning/Storage/Access; D&Rea = Disassembly and Reassembly; Rem = Remanufacturing; Rema = Remake; Reco = Recovery; Recy = Recycling; EoL = End of Life; Ad = Adaptability; St = Standardization; Com = Compatibility; Mo = Modularity; Upg = Upgradability; Su = Sustainability; E = Environment; SR = Social Responsibility; TBL = Triple Bottom Line; Eco = Economic; Env = Environmental; Soc = Social.

were the most recurrent ability's categories. From a TBL perspective, environmental and economic assessments were supported more than social ones.

3.1.3. Circular design decision-support

Based on the fact that there are many design strategies providing practical ways to embed sustainability on products from the beginning of the lifecycle, Gould et al. (2017) proposed a decision-support prototype to choose among them. In order to do this, they conducted a literature review, analysing and selecting the main potential strategies from sustainable product development literature. As a result, they came up with six groups: PSS DfSu, DfRem, design for sustainable behaviour, DfBoP, design for sustainable SC, and design for social innovation.

(Kuo et al. (2019)) proposed a decision-making model to evaluate and implement sustainable PSSs. Comparing the cost of additional durability with the residual value of the product at the end of the lease product, the model tracks both product design and life-cycle cost analysis. Design plays a strategic role in sustainable PSS design, aiming at minimizing negative environmental impacts through resource usage reduction, material recycling and reusing of the products. Indeed, the model wants also to strengthen those DfX strategies embedded into the product design concurring to address sustainable PSSs, mainly DfMA, DfD, DfRel, Quality, Modularity and Variety. These DfX strategies, combined with mathematical models, could support the estimation of product's profit and provide design suggestions strengthening the cradle-to-cradle principle in sustainable PSSs.

(Pozo Arcos et al. (2018)) explored the existing design strategies, guidelines and product features enabling functional recovery operations (as repair, refurbishing or remanufacturing). They also presented a categorization of functional recovery guidelines for product design since they identified the need to plan for recovery at early design stages. Guidelines have been grouped in 4 main classes:

- ease of cleaning supports the use phase
- ease of diagnosis refers to physical inspection
- disassembly and reassembly refers to non-invasive ways to implement repairing and cleaning
- ease of storage refers to keep valuable parts for future usage

Table 6 concerns the category Circular design decision-support: it shows a lack of focus on resource efficiency abilities. Here, researchers concentrated their efforts on both enabling MLC and addressing sustainability, with a social focus. Indeed, MLC and sustainability were the most recurrent ability's categories. Indeed, from a TBL perspective, social approaches were quite integrated to environmental and economic ones.

3.1.4. Design driving circular transition

De Los Rios and Charnley (2017), with the aim of depicting successful sustainable and CE practices being implemented in industry, operated a classification of the DfX/methods supporting the three typical design strategies umbrella terms:

1 Design for life cycle, aimed at:
  a Multiple lifecycles/cradle to cradle: Design for cascaded use, DfRecy, DfRem
  b Longer lifecycles: DfRel, DfMa, Design for Reuse
2 DfE (preventive conservation of material and energy): biomimicry, DfMA, DfSC
3 Whole-system design: radical innovation for sustainability

(Bhamra (2004)) explored the literature concerning eco-design. They identified several factors impelling companies, internally and externally, to pursue eco-design (cost savings, legislative regulations, competition, market pressure, industrial customer requirements, innovation, employee motivation, company responsibility, communications) and reviewed the extant theory and practice of eco-design.

(Rahito et al. (2019)) provided an overview on the characteristics of the existing Additive Manufacturing (AM) technology, focusing on the potential of Direct Energy Deposition technology for repair and restoration of remanufacturable components that can be returned as if they were in new condition or regenerated to match the original specification. In this direction, they suggested the development of design guidelines for restoration of remanufacturable products using AM.

Table 7 concerns the category Design driving circular transition. Researchers neglected to consider approaches belonging to SC, Reliability and Resource Efficiency categories, focusing on either broader and quite consolidated abilities as Design for Lifecycle, Sustainability, Environment, Whole System design or new approaches as Design for AM to support DfRem. Contributions focused mainly on the environmental aspects.

3.1.5. Circular design knowledge management

(Favi et al. (2016)) raised the need to strengthen the connections between the product design and EoL phase. Indeed, so far approaches as DfRem, DfRecy and DfD are only theoretical concepts with few applications within a real industrial context. Indeed, the knowledge of dismantlers and recycling centres is not codified to be used by designers for the re-design of products: even if this kind of design knowledge would be potentially advantaging, an approach to formalize it in practical guidelines is still missing. For this reason, they propose a method to gather knowledge and expertise from dismantler and remanufacturing centres with a focus on the disassembly processes in order to be used during the product design phase: the idea is that the resulting knowledge can be reused for both the specific component but also for the other parts assembled with those elements.

(Toxopeus et al. (2018)) developed a design support tool to provide to designers and engineers with design guidelines for development decisions. They linked product characteristics and reverse cycle processes (reuse, refurbish, remanufacture, recycle) through a disassembly level (product, module, component, material) to foster the resource circulation strategy.

Table 8 describes the Circular Design Knowledge Management category. The two contributions mainly composing this category mainly used approaches aimed at enabling the MLC, and in a minor way also at slowing lifecycle and improve the resource efficiency. The environmental perspective is dominant in this category.

4. Discussion

Wrapping up the results of this research, authors detected five main purposes linked to the application of DfX approaches to foster CE adoption: Circular Design Improvement, Circular Design Metrics and Evaluation, Circular Design Decision-Support, Design Driving Circular Transition, Circular Design KM. In the documents analysed, researchers cited and involved several DfX approaches to address these five main circular design purposes. Due to the high number of approaches and abilities used, in this research the authors decided to divide them in two categories (main and secondary) and took in consideration for their analysis only the main ones. The main approaches have been grouped in five main DfX abilities categories (SC, Resource/Energy Efficiency, Reliability, MLC, Sustainability): they have the aim of synthesizing the multiplicity of words employed to pursue the same ability under a CE perspective. However, also a brief overview of the secondary approaches

Table 6
Circular design decision-support category.

Authors	Objective	Main Abilities														TBL		
		SC	Res/en Eff	Rel		Multiple Life Cycle						Sustainability			Other	Eco	Env	Soc
		C/S SC; SysC	REf&C	SLC; LLUoP; Maint; PLExt	Rel & Sa	MLC; FPD; TecC; BioC; CLPSS; EofC/S/A	D&Rea	Rem; Rema; Reco	Recy	EoL	Ad; St; Com; Mo; Upg	Su	E	SR				
(Gould et al. (2017))	to choose among many design strategies providing practical ways to embed sustainability	x						x				x		x	Sustainable behavior; DfBoP; social innovation.	x	x	x
(Kuo et al. (2019))	to evaluate and implement sustainable PSSs				x		x				x				DfMA; Quality	x	x	
(Pozo Arcos et al. (2018))	functional recovery guidelines for product design						x			x								
Total per ability		**1**	**0**	**0**	**1**	**0**	**2**	**1**	**0**	**1**	**1**	**1**	**0**	**1**	**2**	**2**	**2**	**1**
Total per aggregate abilities		**1**	**0**	**1**		**5**						**2**			**2**			

SC = Supply Chain; C/S SC = Circular/Sustainable SC; SysC = System Change; Res/En Eff = Resource/Energy Efficiency; Ref&C = Resource Efficiency and Conservation; Rel = Reliability; SLC = Slowing Life Cycle; LLUoP = Long Life Use of Products; Ma = Maintenance; PLExt = Product Life Extension; Rel & Sa = Reliability and Safety; MLC = Multiple Life Cycle; FPD = Future Proof Design; TecC = Technical Cycle; BioC = Biological Cycle; CLPSS = Closed-loop PSS; EofC/S/A = Ease of Cleaning/Storage/Access; D&Rea = Disassembly and Reassembly; Rem = Remanufacturing; Rema = Remake; Reco = Recovery; Recy = Recycling; EoL = End of Life; Ad = Adaptability; St = Standardization; Com = Compatibility; Mo = Modularity; Upg = Upgradability; Su = Sustainability; E = Environment; SR = Social Responisibility; TBL = Triple Bottom Line; Eco = Economic; Env = Environmental; Soc = Social.

Table 7

Design driving circular transition category.

Authors	Objective	Main Abilities											TBL			
		SC	Res/en Eff	Rel	Multiple Life Cycle (MLC)				Sustainability				Other	Eco	Env	Soc
		C/S SC; SysC	REf&C	SLC; LLUoP;Rel & Sa Maint; PLExt	MLC; FPD; D&Rea TecC; BioC; CLPSS; EofC/S/A	Rem; Rema; Reco	Recy	EoL	Ad; St; Com; Mo; Upg	Su	E	SR				
De Los Rios and Charnley (2017)	to use DfX/methods to support CE.				x						x		Whole-system design		x	
(Bhamra (2004))	to detect factors impelling companies, internally and externally, to pursue eco-design.									x				x	x	
(Rahito et al. (2019))	to develop design guidelines for restoration of remanufacturable products through the use of AM.					x							DfAM		x	
Total per ability		**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**1**	**1**	**0**	**2**	**1**	**3**	**0**
Total per aggregate abilities		**0**	**0**	**0**	**2**				**1**				**2**	**1**	**3**	**0**

SC = Supply Chain; C/S SC = Circular/Sustainable SC; SysC = System Change; Res/En Eff = Resource/Energy Efficiency; Ref&C = Resource Efficiency and Conservation; Rel = Reliability; SLC = Slowing Life Cycle; LLUoP = Long Life Use of Products; Ma = Maintenance; PLExt = Product Life Extension; Rel & Sa = Reliability and Safety; MLC = Multiple Life Cycle; FPD = Future Proof Design; TecC = Technical Cycle; BioC = Biological Cycle; CLPSS = Closed-loop PSS; EofC/S/A = Ease of Cleaning/Storage/Access; D&Rea = Disassembly and Reassembly; Rem = Remanufacturing; Rema = Remake; Reco = Recovery; Recy = Recycling; EoL = End of Life; Ad = Adaptability; St = Standardization ; Com = Compatibility; Mo = Modularity; Upg = Upgradability; Su = Sustainability; E = Environment; SR = Social Responsibility; TBL = Triple Bottom Line; Eco = Economic; Env = Environmental; Soc = Social.

Table 8
Circular design knowledge management.

Authors	Objective	Main Abilities														Other	TBL		
		SC	Res/en Eff	Rel		Multiple Life Cycle (MLC)					Sustainability						Eco	En	Soc
		C/S SC; SysC	REf&C	SLC; LLUoP; Rel & Sa Maint; PLExt		MLC; FPD; TecC; BioC; CLPSS; EofC/S/A	D&Rea	Rem; Rema; Reco	Recy	EoL	Ad; St; Com; Mo; Upg	Su	E	SR					
(Favi et al. (2016))	to gather knowledge and expertise from dismantler and remanufacturing centers with a focus on the disassembly						x	x	x									x	
(Toxopeus et al. (2018))	to provide to designers and engineers with design guidelines for development decisions to link product characteristics and reverse cycle processes		x	x		x	x		x									x	
Total per ability		**0**	**1**	**1**	**0**	**1**	**2**	**1**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**
Total per aggregate abilities		**0**	**1**	**1**		**6**					**0**				**0**	**0**	**0**	**2**	**0**

SC = Supply Chain; C/S SC = Circular/Sustainable SC; SysC = System Change; Res/En Eff = Resource/Energy Efficiency; Ref&C = Resource Efficiency and Conservation; Rel = Reliability; SLC = Slowing Life Cycle; LLUoP = Long Life Use of Products; Ma = Maintenance; PLExt = Product Life Extension; Rel & Sa = Reliability and Safety; MLC = Multiple Life Cycle; FPD = Future Proof Design; TecC = Technical Cycle; BioC = Biological Cycle; CLPSS = Closed-loop PSS; EofC/S/A = Ease of Cleaning/Storage/Access; D&Rea = Disassembly and Reassembly; Rem = Remanufacturing; Rema = Remake; Reco = Recovery; Recy = Recycling; EoL = End of Life; Ad = Adaptability; St = Standardization ; Com = Compatibility; Mo = Modularity; Upg = Upgradability; Su = Sustainability; E = Environment; SR = Social Responisibility; TBL = Triple Bottom Line; Eco = Economic; Env = Environmental; Soc = Social.

Table 9
DfX, purposes and abilities under a TBL perspective: a general view.

DfX purpose	Number of documents	Main Abilities						TBL		
		Supply Chain	Resource/energy efficiency	Reliability	Multiple Life Cycle	Sustainability	Other	Economic	Environmental	Social
Circular Design Improvement	**15**	2	2	3	15	8	1	8	15	2
Circular Design Metrics and Evaluation	**8**	0	1	2	14	3	0	4	6	2
Circular Design Decision-Support	**3**	1	0	1	5	2	2	2	2	1
Design Driving Circular Transition	**3**	0	0	0	2	1	2	1	3	0
Circular Design KM	2	0	1	1	6	0	0	0	2	0
Total per aggregate abilities		**3**	**4**	**7**	**42**	**14**	**5**	**15**	**28**	**5**

was provided, finding approaches focusing specifically on either the product or the PSS development. Many of them contributed to the SC main category and others to the sustainability (specifically on the materials/energy/waste management and reduction). In addition, the documents were assessed also in terms of TBL perspective of sustainability. This was done to unveil which lenses had been used while adopting specific DfX abilities to address a certain purpose through circular design. These dimensions of analysis are all wrapped-up in Table 9. From the results shown in the table, it stands out in the eyes that the most important purpose to address circularity through DfX approaches is the improvement of products/services/PSSs design (with 15 of 31 contributions). Concerning the DfX abilities, the most used to achieve CE are those oriented to MLC, pushing the concept of lifecycle from a single dimension to multiple circular cycles. Finally, in terms of TBL perspective, the environmental aspect has been the most common one, while the social one has been quite neglected (as already stated in some recent literature reviews on CE, e.g. (Rosa et al., 2019b). More in detail, observing the results from Table 9, the DfX approaches more used to enable circularity are DfRem/Remake/Reco in couple with DfD&Rea. After them, in the same ability category of MLC, some attention has been dedicated also on approaches aimed at both closing the lifecycle loop (as future proof design, Design for Lifecycle (multiple, closed-loop, technical or biological)), and slowing the lifecycle of solutions (as DfMa and DfPLExt). On the other side, also approaches as DfE and DfSu deserved a fair attention: however, they were used as a general and wide category for considering a multiplicity of different more specific functionalities to be addressed under a circular perspective. Finally, only few attempts were done to consider through DfX in the circular design also abilities as SC, the social side of sustainability, resource efficiency and the modularity/adaptability/upgradability of products. These approaches are surely those needing more efforts to be developed extensively.

Finally, once assessed and discussed the state of the art and detected the opportunities, some comments about the gaps in the research context analysed are grasped from Table 10. Aspects claiming further investigation in terms of a more effective transition from linear to circular design through the adoption of DfX approaches have been detected and grouped, also in this case, in 5 macro-classes:

1 *Hybrid strategies and approaches*:
- either to pursue both cost and differentiation strategies,
- or to address both provider product design and user behaviour,
- or to integrate different circular design guidelines in hybrid approaches.

  This kind of gaps are mainly present in two DfX purposes categories (*Circular Design Improvement* and *Circular Design*

Metrics and Evaluation), showing that the ease of circular design is strongly linked to the need of such hybrid approaches providing concurrently different perspectives sometimes also under the same DfX ability umbrella.

2 *Method/Tool*:
- to support design to reduce environmental impact and exploit CE potential,
- to support design decision making towards circular BM, quantitatively assessing circularity (eventually including legislation parameters),
- to provide detailed DfX guidelines with a lifecycle perspective,
- to define a trade-off among needed functionalities and select the most suitable approaches to foster sustainability/CE,
- to understand limitations of single approaches and revolutionize the PSS design process.

  This is by far the most recurring category of gaps in all the five DfX purpose categories, apart *Design Driving Circular Transition*. Indeed, new DfX methods and tools are needed to satisfy quite heterogeneous issues. They are needed either to practically support design decision-making process (also aided by quantitatively indicators) or to find a balance among the several DfX abilities existing or to unveil their single limitations. Sometimes, they can be also required to completely rebuild and restructure the design process of product or PSSs. This category of need is valid if referred either to the general context of DfX adoption in the design process of new products/services/PSSs or to specifically support a more proficient exploitation of CE potentials through design.

3 *Design Knowledge and competencies*:
- to develop more extensively circular DfX approaches and to generate suitable guidelines.

  Such knowledge is strongly needed to enhance both circular design and metrics and evaluation processes. It is also strategic for the DfX purpose category *Design Driving Circular Transition*: indeed, a set of new capabilities, to design sustainable solutions and of new knowledge, are needed as a guidance for manufacturing companies seeking to tackle climate change. Also new design knowledge related to new technologies (as AM) are strongly required to guide the joint pursuit towards CE and Industry 4.0.

4 *Technology*:
- to make product design information/KW available along the SC to pursue a certain BM through a robust information system and single input data sheet,
- to integrate DfX methods/tools with: KM systems (aiding designers in the alternative product solutions definition) and CAD systems (to support the automatic identification of the different product levels (through the topological analysis of product 3D geometry) and to reduce manual inputs),

Table 10
Gaps of DfX approaches in CE research context.

DfX purposes fostering circular economy adoption	Authors	Gaps Categories														
		Hybrid strategies and approaches			Method/Tool					Design KW & competencies	Technology		Design strategies			
		to pursue cost and differentiation strategies	to address provider product design and user behavior	to integrate different circular design guidelines in hybrid approaches	to reduce environmental impact and exploit CE through design	to support design decision making towards CBM	to provide detailed DfX guidelines with a lifecycle perspective	to define a trade-off among functionalities and select the most suitable sustainable/circular ones	to detect single approaches limitations to revolutionize PSS design process	to develop more extensively circular DfX approaches and to generate suitable guidelines	to make design information/KW available along the circular SC through robust information system, CAD and single input data sheet	to develop new technologies to exploit CE potentialities	to foster take-back and reverse logistics,	to quantify the value of resources along the MLC	to define the useful life of products	to define which type of products, need a specific EoL ability and its economic convenience
Circular Design Improvement	(Bakker et al. (2014))							x								
	(Ceschin and Gaziulusoy (2016))								x							
	(Go et al. (2015))				x											
	(Moreno et al. (2016))					x										
	(Pigosso and McAloone (2017))					x				x						
	(van der Laan and Aurisicchio (2019))												x	x		
	(Vanegas et al. (2018))										x					
	(Favi et al. (2019))										x					
	(Wahab et al. (2018))														x	
	(Sundin (2004))															x
	(Hultgren (2012))						x			x						
	(Allwood et al. (2011))														x	
	(Rose (2000))					x										
	(Peeters et al. (2012))															x
	(Arnette et al. (2014))	x	x				x	x		x						
Total per DfX purpose per gap		1	1	0	1	3	2	2	1	3	2	0	1	1	2	2

Table 10 (*Continued*)

DfX purposes fostering circular economy adoption	Authors	Hybrid strategies and approaches			Method/Tool					Design KW & competencies	Technology		Design strategies			
		to pursue cost and differentiation strategies	to address provider product design and user behavior	to integrate different circular design guidelines in hybrid approaches	to reduce environmental impact and exploit CE through design	to support design decision making towards CBM	to provide detailed DfX guidelines with a lifecycle perspective	to define a trade-off among functionalities and select the most suitable sustainable/circular ones	to detect single approaches limitations to revolutionize PSS design process	to develop more extensively circular DfX approaches and to generate suitable guidelines	to make design information/KW available along the circular SC through robust information system, CAD and single input data sheet	to develop new technologies to exploit CE potentialities	to foster take-back and reverse logistics,	to quantify the value of resources along the MLC	to define the useful life of products	to define which type of products, need a specific EoL ability and its economic convenience
Total per DfX purpose per gap category		2			9					3	2		6			
Circular Design Metrics and Evaluation	(Bovea and Pérez-Belis (2004))			x				x		x						
	(Mendoza et al. (2017))				x	x	x	x	x	x						
	(Rocha et al. (2019))			x						x						
	(Rossi et al. (2016))									x						
	(Van den Berg and Bakker (2015))				x	x										
	(Shu and Flowers (1999))															
	(Desai and Mital (2003))															
	(Mayyas et al. (2012))											x				
Total per DfX purpose per gap		0	0	2	2	2	1	2	1	4	0	1	0	0	0	0
Total per DfX purpose per gap category		2			8					4	1		0			
Circular Design Decision Support	(Gould et al. (2017))							x								
	(Kuo et al. (2019))															x
	(Pozo Arcos et al. (2018))							x								
Total per DfX purpose per gap		0	0	0	0	0	0	2	0	0	0	0	0	0	0	1

Table 10 (*Continued*)

DfX purposes fostering circular economy adoption	Authors	Hybrid strategies and approaches			Method/Tool					Design KW & competencies	Technology		Design strategies			
		to pursue cost and differentiation strategies	to address provider product design and user behavior	to integrate different circular design guidelines in hybrid approaches	to reduce environmental impact and exploit CE through design	to support design decision making towards CBM	to provide detailed DfX guidelines with a lifecycle perspective	to define a trade-off among functionalities and select the most suitable sustainable/circular ones	to detect single approaches limitations to revolutionize PSS design process	to develop more extensively circular DfX approaches and to generate suitable guidelines	to make design information/KW available along the circular SC through robust information system, CAD and single input data sheet	to develop new technologies to exploit CE potentialities	to foster take-back and reverse logistics,	to quantify the value of resources along the MLC	to define the useful life of products	to define which type of products, need a specific EoL ability and its economic convenience
Total per DfX purpose per gap category		0			2					0	0		1			
Design Driving Circular Transition	De Los Rios and Charnley (2017) (Bhamra (2004)) (Rahito et al. (2019))								x	x x x		x				
Total per DfX purpose per gap		0	0	0	0	0	0	0	1	2	0	1	0	0	0	0
Total per DfX purpose per gap category		0			1					2	1		0			
Circular Design KM	(Favi et al. (2016)) (Toxopeus et al. (2018))				x						x					
Total per DfX purpose per gap		0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
Total per DfX purpose per gap category		0			1					0	1		0			
Total per gap		1	1	2	4	5	3	6	3	9	3	2	1	1	2	3
Total per gap category		4			21					9	5		7			

- to develop new technologies to exploit CE potentialities.

  Hence, two different types of technology are needed to be enhanced to support the development of DfX in the CE context. From one side, a single repository is needed as a robust information system making knowledge available to the entire extended circular SC. On the other side, new technologies (as AM) need still to be improved to enable a more proficient exploitation of resource circularity, independently from the circular strategy adopted.

5 *Design strategies*:
- to foster take-back and reverse logistics (integrating obsolescence),
- to quantify the value of resources along the MLC,
- to define the useful life of products,
- to define which products need a specific EoL ability and to study the economic convenience.

This kind of gap is quite recurring in the *Circular Design Improvement* DfX purpose category, evidencing the need in the research context not only of new methods, tools, approaches and related knowledge but also of practical strategic solutions to support the pursuit of circular design strategies. Some examples are the easing of take-back and reverse logistic, the quantification of resources value and of the lifespan in the circular lifecycle, and the systematic link of specific abilities to certain types of products also through the verification of the economic convenience of a circular strategy.

Wrapping up, the main gap among those declared in the selected documents is represented by the need of new DfX methods and tools. Through them, quite heterogeneous issues present in the design process must be solved: to practically support design decision-making process (also aided by quantitatively indicators), to find a balance among the several DfX abilities existing and to unveil their single limitations. In some extreme cases, they can be also required to completely rebuild and restructure the design process of product or PSSs, to address servitized and/or circular solutions. Indeed, in a recent research, based on a literature review on DfX approaches supporting the enhancement of products in order to make them more suitable to support the service, (Sassanelli et al. (2016)) defined the Design for Product Service Supportability approach (DfPSSu). Based on it, (Sassanelli and Pezzotta (2019)) developed the PSS Design GuRu Methodology, able to integrate multiple DfX abilities with the aim of systematically designing PSSs and of generating new suitable design knowledge, under the shape of guideline and specific rules. Subsequently, (Ebikake et al. (2018)), included the DfSC in the DfPSSu approach, due to the need of considering the extended SC that is needed to be involved in the realization and provision of PSSs. Given that PSS have been recently detected as one of the most suitable business models to pursue CE (Rosa et al., 2019b), there is great potential to extend the DfPSSu approach with the circular ones detected in this research, leading to the creation of new hybrid approaches (that was detected as another gaps in this analysis). In this way, new circular design guidelines would be generated, protocolled shared and reused, thanks to a robust information system, the design guidelines and rules tool (Sassanelli et al., 2018), that can be integrated in an engineering platform (Pezzotta et al., 2018). This would fill other three types of gaps raised in this article (*Design knowledge and competences, Technology, Design strategies*). It would be able to create new knowledge (mainly under the shape of design guidelines), to exploit the technology needed (a robust IS and a single input data sheet) and to link the different DfX abilities (aimed at enhancing either the service supportability or circularity or both of them) to specific resources, components, product types and industries. Finally, this analysis, assessing the existing knowledge-based design methods as DfX, constitutes a valuable starting point for practitioners (designers and engineers of manufacturing compa-

nies) approaching product/services/PSSs design according to CE paradigm (Sassanelli and Rossi, 2019).

5. Conclusions

This research consisted in a systematic review of the literature with the aim of understanding the real contribution of DfX approaches to the design of circular solutions. First, the purposes of using such type of approaches in the CE research context have been detected: *Circular Design Improvement* and *Circular Design Metrics and Evaluation* are the most explored ones, confirming that DfX approaches are suitable to ease these two strategic processes. The results of the analysis also revealed a certain interest of researchers in using DfX approaches to support some aspects linked to the *Circular Design Decision-Support* and *Circular Design KM* and to better understand the role of *Design Driving Circular Transition*. The analysis of the literature confirms that circular design can be addressed only taking care of multiple abilities in a concurrent way. Due to the high number, approaches and abilities reported in the documents selected in this analysis have been gathered and grouped in five macro areas. They represent the main functionalities to be improved in a product/service/PSS if circularity has to be pursued. *MLC, Sustainability and Reliability* are the abilities that are considered more by researchers, mainly with the aim of either extending the traditional linear product lifecycle (through different circular strategies), or slowing the lifecycle (through the enhancement of inner reliability and security characteristics or making the product more suitable to support those services able to prolong its lifecycle, as maintenance). Instead, approaches related to SC and resource efficiency and conservation still need some efforts to be more extensively explored. This means that design should be more addressed to the design of circular solutions under an Industrial Symbiosis (Neves et al., 2019) lens, enabling to manage better resources information and knowledge in the entire extended SC and thus also improving the resource efficiency throughout the circular MLCs and better define and quantify their changing value in the different phases. These two aspects, DfX purposes and abilities, have also been gauged in terms of TBL. Again, while the environmental perspective is the most considered and the economic one has the role of justifying and evaluating the convenience of circular strategies, the social dimension still needs some efforts to be better defined under a circular perspective. Moreover, only 31 documents were selected in this study, revealing that this is still a niche research context. Most of the contributions are theoretical assessment and in most of the cases literature reviews can provide only frameworks or models or a gathering and classification of DfX abilities and sometimes of their related design guidelines. However, due to the embryonal status of this research context, it suggests several areas of future improvement. The main one is represented by the need of new DfX methods and tools to satisfy quite heterogeneous issues present in the design process: to either practically support design decision-making process (also aided by quantitatively indicators) or to find a balance among the several DfX abilities existing, or unveil their single limitations. A specific and relevant case is represented by the PSS research context, given that PSS are recognized among the most suitable business models to foster CE adoption. Considering that, when dealing with PSSs, DfX approaches are rarely used by experts, this review results can constitute a starting point to detect the DfX approaches that better support a circular PSS design. Finally, from a managerial point of view, the five main categories of abilities detected with this research should be taken in consideration as a fundamental starting point to help companies in moving the first steps towards the CE transition through the design process.

Declaration of Competing Interest

I, along with my colleagues, declare that this manuscript has not been published or presented elsewhere (in part or in entirety) and is not under consideration by another journal. All study participants provided informed consent, and the appropriate ethics review boards approved the study design. All the authors approved the manuscript and agreed with submission to your esteemed journal. There are no conflicts of interest to declare.

Acknowledgements

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