Exploring How Design Can Contribute to Circular Economy Through Design for X Approaches

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Claudio Sassanelli[1[0000-0003-3603-9735]*], Paolo Rosa [1], Sergio Terzi[1]

[1] Politecnico di Milano, Department of Management, Economics and Industrial Engineering, Piazza Leonardo da Vinci, 32, 20132, Milano, Italy
claudio.sassanelli@polimi.it, paolo1.rosa@polimi.it, sergio.terzi@polimi.it

Abstract.
Design plays a strategic role for companies in addressing servitization and Circular Economy (CE) paradigms, to deliver either products, or services or Product-Service Systems (PSSs). Design for X (DfX) practices, belonging to concurrent engineering approach, have revealed great effectiveness in enriching products with functionalities as service supportability and circularity. They have been also used to systematize PSSs components along the design process, enabling and easing design knowledge creation and sharing between product and service designers. Nevertheless, notwithstanding the abundance of DfX approaches related with the End of Life (EoL) stage, they still lack of a CE perspective. Therefore, this paper wants to explore how design can contribute to CE through the use of DfX approaches.

Keywords: Circular Design; Design for X; Circular Economy; End-of-Life; Design Guidelines; Knowledge Management

1. Introduction

Two upcoming factors are affecting product manufacturers. Firstly, Circular Economy (CE) [1], highlights the always more worrying natural resources scarcity. Secondly, servitization [2], leads towards a more sustainable economy [3], through the advent of the sharing economy and the delivery of product-related services [4]. Going ahead with this transition, companies have also to enact a business model shift [5], [6], leading hurdles [7] and potential benefits [8]. However, the integration of product-services under a circular perspective still need suitable methods and tools. Specifically, Design for X (DfX) guidelines [9], belonging to the concurrent engineering context, can enable the design of products/service/systems to address requirements (e.g. features, performance, constraints, etc.) pursuing specific DfX abilities. DfX approaches are very successful in improving competitiveness measures and rationalizing design decisions in product development [9]. They have been also used to systematize PSSs components along the design process, enabling and easing design knowledge creation and sharing between product and service designers [10], [11]. Furthermore, several DfX methods and tools already focus on the End of life phase, but lack of a CE focus [12]. The aim of this work is understanding the role of design along the CE transition through the use of DfX approaches. The paper is organized as follows. Section 2 describes the adopted research methodology. Section 3 presents results coming from the literature review and Section 4 discusses them. Section 5 provides conclusions and future research trends.

2. Research methodology

A literature review [13], [14] on scientific articles published up to the third quarter of 2019 and gathered from Science Direct® and Scopus® has been carried out. The keywords “Circular Economy” and “end of life” have been combined with either “Design for X”, “DfX” or “design guideline” and searched without any time/document restriction. Searches led to 741 results. Furthermore, 25 documents were found through cross-referencing and 4 by hand search. 15 additional documents have been recommended by experts and serendipity. After having excluded: i) grey literature, ii) non-English contributions, iii) redundancies, iv) unfitting papers (by title/abstract check) and v) unfitting papers (by full-text check), a total of 31 articles have been selected. An assessment of results unveils that about 60% of these papers have been published from 2015 onwards. European experts contributed more in this context (71%), followed by North Americans (16,1%) and Southeast Asian/Chinese ones (12,9%). Most of the selected contributions provided a theoretical perspective of the context. Indeed, more than half of the documents (19 of 31) provided just a theoretical interpretation of the link between DfX approaches and the circularity paradigm. Instead, 12 of them proposed case studies and application cases to strengthen their researches from an empirical point of view. Here, the most cited products/industries where circular DfX have been applied are Electrical and Electronic Equipment and automotive sectors.

3. Results: DfX approaches supporting CE adoption

The literature review led to the understanding of relationships among DfX abilities and CE. Contributions have been grouped according to 3 different drivers (Table 1):

- DfX purposes supporting CE, grouped in 5 categories (circular design improvement, circular design metrics and evaluation, circular design decision support, design driving circular transition, circular design knowledge management), to understand how design contributes to the circular transition through the adoption of DfX approaches;
- Ability/ies addressed (Supply Chain (SC), Resource/energy efficiency, Reliability, Multiple Lifecycle, Sustainability), detailed in Table 1,
- Triple Bottom Line (TBL) perspective (economic, environmental, social).

Table 1. Categorization by DfX purposes, DfX Abilities, TBL perspective

DfX purposes	Authors	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; Ma; 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				
Circular design improvement	Bakker et al. (2014)		x	x				x	x	x						x	x	
	Ceschin and Gaziulusoy (2016)											x				x	x	x
	Go et al. (2015)					x											x	
	Moreno et al. (2016)	x	x	x		x											x	
	Pigosso and McAloone (2017)					x									x	x	x	
	van der Laan and Aurisicchio (2019)					x										x	x	
	Vanegas et al. (2018)						x									x	x	
	Favi *et al.* (2019)						x		x							x	x	
	Wahab et al. (2018)				x			x								x	x	
	Sundin (2004)							x					x				x	
	Hultgren (2012)						x		x			x	x				x	
	Allwood et al. (2011)							x									x	
	Rose (2000)												x				x	
	Peeters *et al.* (2012)						x										x	
	Arnette, Brewer and Choal, (2014)	x										x	x	x		x	x	x
Circular design metrics and evaluation	Bovea and Pérez-Belis (2004)						x	x	x	x			x				x	
	Mendoza et al. (2017)			x		x	x				x						x	
	Rocha et al. (2019)											x				x	x	x
	Rossi et al. (2016)		x				x	x									x	
	Van den Berg and Bakker (2015)			x		x	x	x									x	
	Shu and Flowers (1999)							x								x		
	Desai and Mital (2003)						x									x		
	Mayyas et al. (2012)											x				x	x	x
Circular Design Decision-Sup-port	Gould et al. (2017)	x						x				x		x	x	x	x	x
	Kuo et al.(2019)				x		x				x				x	x	x	
	Pozo Arcos et al. (2018)						x			x								
Design Driving Circular Transition	De Los Rios and Charnley (2016)					x							x		x		x	
	Bhamra (2004)											x				x	x	
	Rahito, Wahab and Azman (2019)							x							x		x	
Circular Design KM	Favi et al. (2016)						x	x	x								x	
	Toxopeus et al. (2018)		x	x		x	x		x								x	

- 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= Compatibil-ity; Mo= Modularity; Upg= Upgradability;
- Su= Sustainability; E= Environment; SR=Social Responisibility; TBL=Triple Bottom Line; Eco=Economic; Env= Environmental; Soc= Social.

Circular design improvement

[12] evaluated how product life extension and product recycling can be addressed by product design. To decide when to apply a specific strategy (prevention, reuse and recycling), they presented a methodology defining the optimal product lifespan and applied it to two case studies on a domestic refrigerator and a laptop. [16] explored how Design for Sustainability (DfSu) approach grew, gathering design approaches in four innovation levels: Product, Product-Service System (PSS), Space-Social and Socio-Technical System. To this aim, they assessed DfX guidelines and toolkits suitable with sustainable attitudes. [17] presented a framework for CE design strategies, assessing the literature on DfSu and circular business models and finding five main circular design strategies plus ten circular design recommendations. [18] defined Design for Multiple Lifecycle (DfMLC) as a mix of eco-design strategies. They provided the main guidelines of all the DfX approaches considered, promoting their concurrent adoption for the circular design application. [19] detected three main design topics in the CE context. Among them, PSS seems to be a strategic for CE adoption, especially if coupled by design guidelines and sustainability evaluation methods. [20] formulated 10 guidelines for the design of closed-loop PSSs. [21] proposed a method, “eDiM” (ease of Disassembly Metric) to measure ease of disassembly and recoverability and compare design alternatives. An LCD monitor case study was conducted. [15] created a Design for Disassembly method and tool to support the implementation of re-design improving product de-manufacturability and EoL performances. The LeanDfD package can assess design decisions, store and classify disassembly data (standard times and corrective factors of each disassembly liaison and operation) to create valuable knowledge. [22] detected Design for Remanufacturing as the enabler for life cycle reliability and safety. A relevant issue related to this work is to predefine the useful life of products already in the development phase to further assess the reliability and safety of the product along their MLCs. [23] proposed the RemPro-matrix, studied Design for Environment and Design for Remanufacturing, identifying the most important related product properties and their relationship with the remanufacturing process phases. Several application cases with remanufacturers were conducted. [24] formulated, through application cases in consumer electronics industry, 4 guidelines and 14 design strategies on recyclability to help engineers in designing products that are easier to recycle. [25] proposed four strategies for managing material demand through material efficiency, trying to provide directions for this research context through a list of 20 open questions: the main one was to verify the possibility for companies/industries/countries to raise competitiveness and prosperity through improving material efficiency. [26] proposed a design tool, End-of-life Design Advisor, leveraging on designers’ and product managers’ recycling experiences to take EoL strategy decisions. By conducting 37 case studies, she detected six final technical product characteristics (wear-out life, technology cycle, level of integration, number of parts, design cycle, reason for redesign). [27] grouped design guidelines for the demanufacturing strategies and categorized three types of products to be considered in the remanufacturing process: PSS-based products; electronic products; products to be not repaired, remanufactured or refurbished. [28] highlighted that PSS’s product components lead manufacturers or retailers to implement demanufacturing improvements and grouped DfX approaches in four categories under the DfSu umbrella.

Circular design metrics and evaluation

[29] organized, from a CE lens in five circular design groups, 46 design guidelines derived from them the eco-design framework and DfX approaches, also proposing new guidelines. A methodology was proposed to check if a product design meets the design guidelines required from a CE perspective. The methodology was applied on twelve case studies, defining two main criteria to define circularity degree (margin of improvement and relevance). [30] categorized product design and business model strategies in two main actions, slowing and closing resource loops. They also identified several gaps related to the adoption of DfX approaches related to design sustainable and circular products. [31] proposed an analytical framework for DfSu models. They found that several are the attempts to support companies in implementing DfSu, either for products or service or PSS development. However, the link between this approach and CE has still to be adequately studied, as suggested by the majority of the political agendas to foster environmental sustainability without compromising economic growth. [32] conducted a review of eco-design methods and tools to allow CE industrial application. 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. [33] proposed a CE framework from a product design perspective performing a review of the extant CE terminology. They defined five most design-relevant topics and detected two main streams (futureproof and disassembly). A B2B indoor LED lighting was used as a case study in the tools development. [34] explored remanufacturing and its conflicts with other DfX approaches, detecting six processes to ease this process and proposed a framework to quantify costs. The framework has been tested on photocopiers and toner cartridges. [35] proposed a methodology performing calculations that allow the detection of disassembly anomalies, design modifications and finally also disassemblability improvement. They tested the effectiveness of the methodology to verify the disassemblability of an electric drill. [36] made a review of the literature on vehicles' life cycle, disposal and end of life analyses, declining DfSu into 4 main groups.

Circular design decision-support

[37] proposed a decision-support prototype to select design strategies, defining them through a literature review in six main groups. [38] developed a decision-making model to assess and implement sustainable PSSs, tracking both product design and life-cycle cost analysis. A heat-pump water heater case study was conducted to generate product selling and leasing model design suggestions and facilitate sustainable servitization through development considerations. [39] proposed a categorization of functional recovery guidelines for product design based on the need to plan for recovery at early design stages. Guidelines have been grouped in 4 main classes: ease of cleaning, ease of diagnosis, disassembly and reassembly, ease of storage.

Design driving circular transition

[40] classified the DfX/methods considered successful for sustainable and CE practices under three typical design strategies umbrella terms: Design for life-cycle, Design for

the environment, Whole-system design. [41] identified several factors impelling companies, internally and externally, to pursue eco-design. [42] focused on the potential of Direct Energy Deposition technology for repair and restoration of remanufacturable components. They suggested the development of design guidelines for restoration of remanufacturable products using Additive Manufacturing.

Circular design knowledge management

[43] evaluated the link between product design and EoL phase. They propose a method to gather knowledge and expertise from dismantler and remanufacturing centers with a focus on the disassembly processes to be used during the product design phase. [44] proposed a design support tool to cater designers and engineers with design guidelines for development decisions. They linked product characteristics and reverse cycle processes through a disassembly level to support the resource circulation strategy.

4. Discussions

From the analysis of the article selected in this review, DfX main purpose to address circularity is the enhancement of the design of solutions. In addition, the most adopted DfX abilities to sustain CE belong to the MLC domain, impelling the concept of lifecycle from a single cycle to multiple circular ones. It has also to be highlighted that most of the contributions gave evidence to several gaps hindering the corroboration of this twofold DfX-CE research context. Indeed, first of all they claimed that the extant DfX tools and methods should be revitalized since companies have difficulties in practically use eco-design tools and methods. New tools are requested to:

- better support designers and engineers to take decisions and actually implement the circular product/service BM, and a combined quantitative assessment to measure how the circular design is applied to different products and BMs;
- support the reduction of product environmental impact through MLC design;
- provide detailed design guidelines and strategies for engineers to address recycling and close the materials loop in a easy to apply and evaluate way;
- provide strategic directions linked to environmental performance;
- integrate and rank the several DfX strategies;
- define a preference among the abilities/guidelines considered and find the best trade-off between product requirements;
- revolutionize the way in which products and services are developed;
- strengthen the connections between the product design and EoL phase.

From a strategic and BM perspective, the main issues were:

- to understand how to integrate obsolescence,
- to develop design strategies to foster take-back services and reverse logistics;
- to understand the value of resources used in PSSs (that change over time);
- to define which type of products need a specific EoL ability;
- to align the product development with supply chain and BM to exploit CE.

Instead, under a technological lens, there is a lack of a robust information system, leveraging on a single input data sheet, to make product design information, provided by

OEMs, available along the supply chain to pursue a certain circular BM, to optimize the EoL process and simultaneously gauge multiple eco-design performances. Also the knowledge management domain needs strongly improvements. Among all, it has to be highlighted the urgent need to integrate the circular design guidelines aiming at extending life span with those related with component reuse. In particular, extant DfX guidelines and techniques do not foster the use of product design information along business planning and decision-making processes at systems-level. All these issues, calling for a more effective transition from linear to circular design through the adoption of DfX approaches, could be better analysed and grouped with the aim to be addressed in a more effective way. Wrapping up, the main gap seems to be the necessity of new DfX methods and tools. Their provision would solve different issues along the design process: to aid design decision-making process (also through quantitative KPIs), to balance out the heterogeneous DfX abilities (also revealing their proper shortcomings and limits), to re-enact the design process itself and focus its attention on specific perspective, service supportability and circularity. This would help also under several perspectives (knowledge management, competences, Technology, strategic). Indeed, new methods could be useful to create new knowledge (structured in design guidelines), to coalesce the different DfX abilities needed and to fully take advantage of the technology used (information systems and unique input data sheet).

5. Conclusions and further researches

This research operated a literature review to evaluate how DfX practices can contribute to the design of circular solutions. This research context is still very limited, since only 31 contributions were selected, and the majority of the contributions are either theoretical assessment or literature reviews (providing frameworks, models, classification or design guidelines pertaining the DfX abilities involved). The author of this research detected five main purposes of using DfX in the CE research context: *Circular Design Improvement, Circular Design Metrics and Evaluation, Circular Design Decision-Support, Design Driving Circular Transition, Circular Design KM.* Among them, the first two are the most recurrent, confirming the traditional roles of DfX approaches. This research confirms that circular design can be addressed only addressing several abilities in a hybrid way. A high number of DfX approaches was detected, leading to their gathering in five macro areas (representing the main functionalities to be considered in a product/service/PSS if circularity has to be addressed): *Supply Chain, Resource/Energy Efficiency, Reliability, MLC, Sustainability*. Among them, the last three are those more considered by researchers to prolong or slow the linear product lifecycle. While, the first two need more investigations. Moreover, DfX abilities and their purposes have been assessed under the TBL perspective: confirming what presented in recent literature reviews on CE, the social aspect still needs to be further explored. Finally, several gaps have been revealed in these research contexts, revealing that there is room for future investigations. Among them, new hybrid DfX methods and tools can address several problems concerning the design process, either in the design decision-making process or in balancing the several DfX abilities required. An interesting case is revealed by the

PSS research context, recognized as one of the most important BM to apply CE but where DfX approaches are rarely used by experts. The five macro areas of abilities can be the basis to select the DfX approaches that could foster a circular PSS design process.

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