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HOW CAN DESIGN SCIENCE CONTRIBUTE TO A CIRCULAR ECONOMY?

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Abstract

Circular Economy is increasingly seen as a key approach to operationalising goals and supporting the transition to a sustainable society by enhancing competitiveness and economic growth. Creating a Circular Economy requires fundamental changes throughout the value chain, from innovation, product design and production processes all the way to end of life, new business models and consumption patterns. This paper explores how design science can support the transition from the traditional linear 'take-make-consume-dispose' approach, to a Circular Economy. By means of a systematic literature review, this paper discusses the role of a set of design topics in this transition.

Keywords: Circular economy, Sustainability, Design for X (DfX)

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1 INTRODUCTION

The current linear economic system, based on value creation by "taking-making-using-disposing" (Kowalski and Weizsäcker, 2011), is increasingly showing signs of its economic and environmental risks in the long-term (Steffen and Smith, 2013). In response to the unsustainability of the linear economic system, Circular Economy is increasingly seen as a key approach to supporting the transition to a sustainable society by enhancing competitiveness and economic growth (Ellen MacArthur Foundation, 2012).

Circular Economy is based on the establishment of multiple value creation mechanisms, which enables manufacturing companies to decouple enhanced business success and revenue growth from the consumption of finite resources (Ellen MacArthur Foundation et al., 2015). By doing that, Circular Economy has the potential to enable resource efficiency, closed-loop systems (with enhanced remanufacturing, reuse and recycling), job creation and enhanced sustainability performance throughout the value chain and products' life cycles.

Creating a Circular Economy requires fundamental changes in the business processes of a varied set of stakeholders throughout the value chain including product design and development, manufacturing and operations, direct and reverse logistics, consumption patterns, business models (EEA, 2016) and so on. Engineering design and product development are often mentioned as key factors to support the transition towards a Circular Economy (Laurenti et al., 2015; Moreno et al., 2016). In order to be able to provide value in a closed-loop economy, products/services need to be designed and developed in a way to allow extended lifetime, recyclability and re-manufacturability, modularity, enhanced robustness, adaptability, etc. (Bakker et al., 2014; Tukker, 2015). Current product design is facing a new challenge of anticipating social, economic and environmental challenges to realise the goals of a Circular Economy (Singh and Ordoñez, 2016).

This paper explores how the transition from the traditional Linear Economy to a Circular Economy can be supported by design science. By means of a systematic literature review, this paper discusses the role of a set of design-related topics in this transition, from the perspective of the emerging Circular Economy research community. Research gaps are identified with the view of expanding design science towards a Resource-Sensitive Design.

2 RESEARCH METHODOLOGY

A systematic literature view was carried out in this research with the ultimate goal of exploring the role of design science in supporting the transition to a resource-efficient and circular economy. Systematic reviews provide a structured way to exploring a given research topic, enhancing the replicability and traceability of the obtained results (Biolchini et al., 2005).

The review protocol was organized in three main areas: data collection, data analysis and reporting. *Data collection* included the definition of the research objective, search strings and keywords and scientific databases. With the objective of understanding the role of Design Science in Circular Economy, the following search string was defined (("circular economy") AND ("design" OR "development" OR "innovation") AND ("product" OR "service" OR "system")).

Studies were identified in two databases: Scopus and Web of Science, due to their academic relevance to the topic. The review was carried out in December 2016 and was limited to journal articles in English. In total, 217 articles were identified in Scopus and 97 articles were identified in Web of Science. By means of applying excluding criteria (i.e. articles discussing Circular Economy from a design perspective), 17 unique articles were selected for data analysis and reporting, based on title/abstract screening.

Data analysis of the selected studies included the definition of the key information to be collected and the procedure for analysis. In this study, the information obtained from the selected articles was classified based on the conference topics for ICED17, which provide a comprehensive list of topics that are relevant for design science (Table 1).

Reporting included the definition of the descriptive analyses performed in the research, and included the yearly distribution and publication sources, and a cross-analysis of the role of design science for Circular Economy based on the defined topics, together with the identification of potential research gaps. The results are presented in the next section.

Table 1: Classification criteria based on the conference topics for ICED17

Design processes	Models, strategies and process modelling
Design organisation and management	Organisational understanding, market and business implications and social responsibility
Design research application and case studies	Industry case studies, design practice and applications of design research across industry domains
Products, services and systems design	Platform design, design and optimisation of organisational processes and product/service-systems (PSS)
Design methods and tools	Requirements elicitation and management, evaluation and decision-making and bio-inspired design
Design for X	Ecodesign, design for lifecycle and design for properties
Design information and knowledge	Information and knowledge management, knowledge-intensive design, and design knowledge and collaboration
Design theory and research methodology	Design theories and approaches, research methodologies and methods and experiments in design
Human behaviour in design	Design cognition, design for emotion and experience and creativity and innovative thinking
Design Education	Industry training, teaching examples and experiments and life-long learning in design

3 RESULTS

In this section, the role of design science for Circular Economy is discussed based on the results obtained by means of the systematic literature review. Starting with an overview of the selected articles, this section presents the discussion of Circular Economy within each design topic, as presented in Table 1.

3.1 Overview of the selected articles

Circular Economy is a relatively recent research field, with the concept being coined in early 2012 by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2012). Based on the analysis of the distribution of the identified articles over the last few years, it is possible to observe a significant number of publications dealing with Circular Economy in 2016 (70% of the selected articles).

While this study deliberately focused on the identification of papers explicitly dealing with Circular Economy (which is evident by the search string), it is important to note that the concept of Circular Economy is based upon a set of complementary and synergic research fields, which have been important research topics over the last 20+ years. Research fields that contributed to coining the Circular Economy concept include sustainable design (Spangenberg et al., 2010) and ecodesign (Stevels, 2001), life cycle thinking (Fava, 1998), product/service-systems (Sousa and Miguel, 2015), industrial ecology (Yu et al., 2013), business model innovation (Esslinger, 2011), Cradle to Cradle (Braungart et al., 2007), among others. Due to the scope defined in this research, these studies were not intentionally included in the review. With the large majority of articles published by the Journal of Cleaner Production, it becomes apparent that the researchers dealing with Circular Economy mainly have sustainability and environmental research backgrounds. The other journals range across a large variety of research topics, with only two articles being published in journals related to design science (Design Studies).

3.2 Overview of design topics in a Circular Economy context

3.2.1 Design processes

In the identified articles, a limited focus is attributed to design models and design process modelling and management. While the integration of Circular Economy in the early design process is highlighted (Bocken et al., 2016), descriptive research on the inclusion of ecodesign practices in product development, based on large-scale surveys, can be observed (Sihvonen and Partanen, 2015).

Furthermore, initiatives for the definition of design strategies and guidelines that can be applied for the development of circular products are proposed. Building upon previous research, Bocken et al (2016) introduce three main strategies for Circular Economy: slowing resource loops, closing resource loops and resource efficiency or narrowing resource flows - which implies in a set of specific strategies for circular design (e.g. designing long-life products, design for product-life extension, design for dis- and reassembly, etc.). Based on literature review and consolidation of existing frameworks of related concepts (such as ecodesign) and circular business models, a set of circular 10 design guidelines are proposed by (Moreno et al., 2016). Guidelines include systems change, new circular business models, revolution thinking, design for multiple life cycles, living and adaptive systems, co-development in the value chain, value in a broader view, design with failure in mind, design knowing where each material and parts come from and where goes to, and design with "hands on" experiences (Moreno et al., 2016).

3.2.2 Design organisation and management

Business models that can enable the transition towards a Circular Economy are extensively explored in the research field. Research is focused on identifying the typologies of circular business models (Lewandowski, 2016), establishing their relations with product design (Moreno et al., 2016) and defining ways to support companies in the design, test and implementation of those business models (Bocken et al., 2016). Bocken et al. (2016) propose a set of business model strategies for slowing loops (access and performance model, extending product value, classic long-life model and encourage sufficiency) and for closing loops (extending resource value and industrial symbiosis), with a set of industrial examples. The authors argue that design and business model strategies need to be implemented in conjunction in order to fully capture the business potential of the Circular Economy - and should be based on a common overarching vision. Designers' role in the development of circular business models lies in providing the understanding of the factors that can influence consumer acceptance of new ownership models and other product/service-systems (Bakker et al., 2014).
In order to support the design of circular business models and their implementation, a Circular Transition Framework is proposed by Scheepens et al. (2016). Although social responsibility of design is touched upon (Winans et al., 2017), in-depth studies dealing with the topic could not be identified in the set of articles analysed in this study. Similarly, organisational understanding, workspaces for design, management of innovation and complexity and assessment and management of risks and uncertainties are only briefly discussed.

3.2.3 Design research application and case studies

Since design for Circular Economy is still in its early development stages, which is characterized by exploratory and descriptive studies, a limited focus could be observed on design research application and case studies (i.e. there is a limited transfer of design methods into industry).
Nevertheless, it is important to note that there is an impressive set of cases demonstrating Circular Economy in an industrial environment, in a varied set of sectors and with different companies sizes and geographical distribution (Bocken et al., 2016). Similarly, Singh and Ordoñez (2016) analysed over 50 examples of products developed from discarded materials, categorising them into Circular Economy recovery routes, which enabled the identification of practical challenges for the implementation of Circular Economy. Case studies related to upcycling in the fashion industry in the UK enabled the identification of best practices and key leveraging points (Han et al., 2014).
These cases provide success stories and inspiration for companies moving towards circularity and supports the development of the research field with the identification of patterns and best practices.

3.2.4 Products, services and systems design

Product/Service-Systems (PSS) are often mentioned as a promising approach to enable a Circular Economy (Tukker, 2015), as they provide a set of opportunities to enable dematerialization, to decouple value creation from product consumption, and to enhance competitiveness (Ceschin and Gaziulusoy, 2016; Loiseau et al., 2016).
By keeping ownership of the physical products (which happens in use- and/or result oriented PSS (Tukker, 2004)), manufacturing companies have additional incentives to developing more durable and serviceable products, to take them back at the end-of-use and to define the best strategy for reuse, remanufacturing, recycling, etc. (Scheepens et al., 2015; Tukker, 2015).

From a design perspective, the identified papers focus on understanding how different PSS typologies can contribute to Circular Economy and on defining their links to product design (Moreno et al., 2016). Furthermore, systems thinking is recognized as a key capability of designers dealing with Circular Economy, as the design process should involve a system perspective on the product life cycle and its entire value chain - with the identification and mitigation of potential rebound effects (Moreno et al., 2016; Scheepens et al., 2015). The Eco-costs/Value ratio method is presented as an approach to support the evaluation of the environmental performance and potential rebound effects of PSS (Scheepens et al., 2015).
Recently, "Upgradable PSS" has been introduced as an approach that enables the development of offers without ownership transfer that facilitates the implementation of Circular Economy (Pialot et al., 2017), this combines upgradability with optimised maintenance, with valorisation of end-of-life parts and servitization of the offer (Pialot et al., 2017). Product and systems modelling, product architectures and product family design, design and optimisation of organisational processes were not discussed in the identified articles.

3.2.5 Design methods and tools

An extensive exploration of design methods and tools related to Circular Economy could be identified in the selected articles. It is argued that design principles, methods and tools from sustainability-related disciplines can support the design and development of closed-loop products (Moreno et al., 2016).
The need for supporting the selection of critical materials (in terms of vulnerability to supply restriction, supply risk and environmental implications) during product design and development is discussed (Peck et al., 2015). Bio-inspired design and biomimetic are also mentioned as approaches that can be used as an ecological standard to judge the "correctness" of innovations (Ceschin and Gaziulusoy, 2016). While the need for the development of specific methods and tools for circular design are mentioned (Bocken et al., 2016), there is still little research on the development and implementation of such methods.
One example of methodology development is related to the definition of an approach to support the determination of the optimal product lifespan (Bakker et al., 2014), especially applicable for energy-using products. The optimal product lifespan is defined as the time in which environmental impacts related to the product use equals the impacts of a replacement product (Bakker et al., 2014). Involvement of end-users and customers in the development of circular products is also mentioned as an important factor (Moreno et al., 2016).
By linking sustainable public procurement and sustainable business models, the research concludes that the collaboration between procurers and suppliers can support the transition towards a Circular Economy (Witjes and Lozano, 2016). Some authors argue that although methods and tools for a large variety of the design strategies already exist (e.g. design for recycling, design for remanufacturing and design for end-of-life), they might need to be adapted to a circular design context (Bakker et al., 2014).
Furthermore, Laurenti et al. (2015) argue that information technology and computer-aided design (CAD) tools should be refined in order to support circular design. Some of the proposed features include: guide user behaviour towards increased product lifetime and reuse; design in a way that decreases material stock in the use phase and considering material; and design concept choices so that material flows are kept clean (Laurenti et al., 2015).

3.2.6 Design for X

A large variety of Design for X are recognized as having an important role in the design of circular products. Design for Environment and Design for Remanufacture, which lead to other design strategies such as Design for Upgrade, Design for Assembly, Design for Disassembly, Design for Modularity, Design for Maintainability and Design for Reliability are mentioned by Moreno et al. (2016). Furthermore, Moreno et al. (2016) defined three overarching specific DfX for Circular Economy: Design for Resource Conservation, Design for Slowing Resource Loops and Whole Systems Design, which is deployed into five Circular Economy Strategies, nine design focuses and twenty five DfX methods/tools.
The use of digital technologies, Internet of Things (IoT) and big data are increasingly discussed as enablers for Circular Economy (Reuter, 2016). Design strategies for product life extension are discussed by Bakker et. al (2014), following the hierarchy (material efficiency > longer product life > reparability > refurbishment > remanufacture > recycling).

Furthermore, it is recognized that the design of circular products will have considerable impact on the design of a product, due to the new requirements to be fulfilled, especially in relation to functional, emotional, aesthetic and economic considerations (Bakker et al., 2014).

3.2.7 Other design topics

Significant contributions to the design topics related to "Design information and knowledge", "Design theory and research methodology", "Human behaviour in design" and "Design education" were not identified in the articles analysed in this research.

3.3 Visualizing design topics in a Circular Economy context

Figure 1 provides a summary of the key findings presented in section 3.2 and an illustrative visualisation of the relative importance (RI) of the explored design topics in a Circular Economy context. The relative importance is based on a Likert scale ranging from 1 (relative low importance) to 5 (relative high importance). Importance is allocated based on the author's subjective assessment of current research on Circular Economy, based on the articles included in this review. Our main goal is to support the visualisation of the results obtained in this paper.

4 DISCUSSION AND FINAL REMARKS

Based on a systematic literature review, this paper has discussed the role of Design Science in supporting the transition towards a Circular Economy by taking into account a varied set of design topics, from the perspective of the Circular Economy research community. The literature review provides an understanding of the current research developments on Circular Economy, and the elucidation of key design areas that are currently being explored by the Circular Economy community.

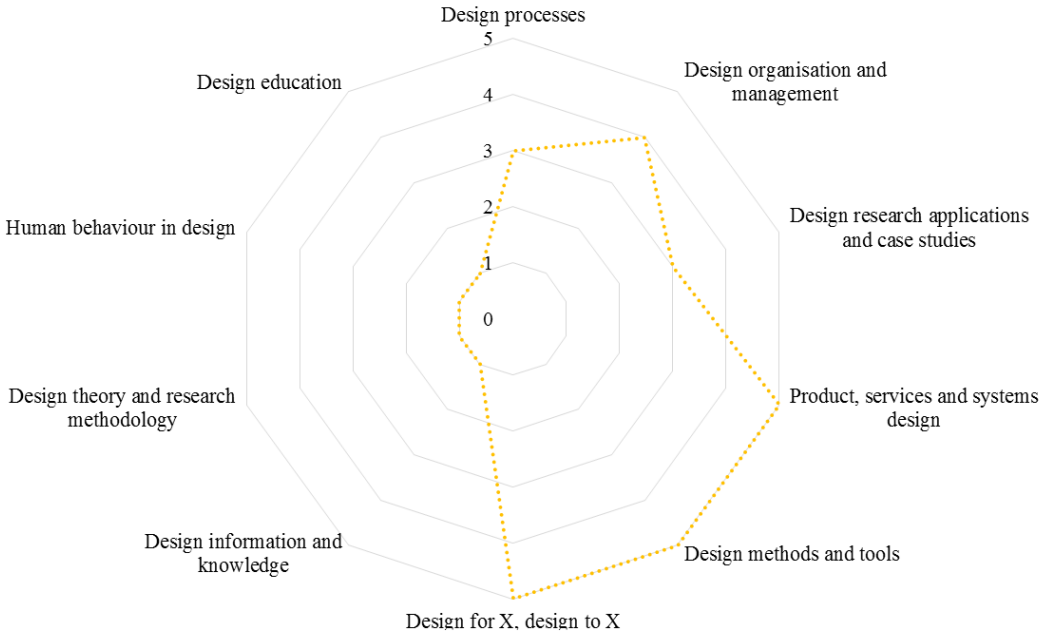
Three design science topics have been highlighted that seem to be especially important to support the transition towards a Circular Economy: "Product, services and systems design" (with strong focus on PSS); "Design methods and tools"; and "Design for X, design to X". Furthermore, business models for a Circular Economy appears as a promising research area. It is a gap of research in design topics dealing with design information and knowledge (which seems especially relevant in a digital technology context), design theory and research methodology, human behaviour in design and design education.

The identification of future research in the intersection of Design Science and Circular Economy can be performed based on some of the key challenges identified in the literature review (Bakker et al., 2014; Laurenti et al., 2015; Singh and Ordoñez, 2016; Winans et al., 2017):

- lack of control or accurate prediction of the composition of the waste streams available, as products can be handled very differently in their use and end-of-life phases;
- change of material composition of waste streams seasonally, over time and depending on the location where the waste is collected;
- lack of integration of broader aspects (such as cultural values) into the design process;
- lack of approach to enable that conventional product quality standards apply to the products made from recovered materials;
- lack of an approach to holistically address product complexity;
- lack identification and mitigation of unintended environmental consequences of design;
- lack of an approach to deal with the enhancement of technology obsolescence and design redundancy;
- lack of assessment of the value of Circular Economy for specific value chains, material flows and products;
- lack of the evaluation of sustainability potential of circular solutions.

Based on the vertiginous increase of research related to Circular Economy in 2016, it is expected that the following years will be decisive for the maturation of the research field and its connection with design science. It is expected that more research will be developed on the aforementioned topics.

The scope of this article was defined in a way to enhance the understanding of how Circular Economy researchers perceive the role of design science to support the transition towards Circular Economy. Future research should focus on a complementary view, which would look at how the design science community understands their contribution to a Circular Economy, based on the robust body of knowledge developed over the last decades.



	RI	Key research areas
Design processes	3	- integration in the early stages - definition of circular design strategies and guidelines
Design organisation and management	4	- circular business models (typologies and design strategies) - design and implementation of circular business models - designers' role in circular business models - social responsibility of design
Design research applications and case studies	3	- exploratory and descriptive case studies - large set of cases demonstrating Circular Economy in industry - Success stories, inspiration, challenges and best practices
Product, services and systems design	5	-PSS as a promising approach for Circular Economy - PSS typologies and design guidelines - Systems thinking and rebound effects identification/mitigation - PSS sustainability evaluation
Design methods and tools	5	- sustainability-related methods and tools can support circular design - support selection of critical materials - bio-inspired design and biomimetic - need of specific methods and tools for circular design - co-creation and collaboration
Design for X, design to X	5	- key role of DfX in circular design - use of digital technologies, IoT and big data as enablers for a circular economy - impact of circular economy in traditional DfX (e.g. cost, aesthetics, performance)
Design information and knowledge	1	-
Design theory and research methodology	1	-
Human behaviour in design	1	-
Design education	1	-

Figure 1. Summary of key findings and visualisation of the relative importance (RI) of the design topics in a Circular Economy context

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