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Melanie Jaeger-Erben

Nils F. Nissen (eds.)

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(In alphabetical order of first authors)

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A multi-hierarchical "Design for X" framework for accelerating circular economy

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Keywords: Design for X; Collaborative Design; Interdisciplinary Approach; Circular Framework; Design Tool.

Abstract:
In the past, many frameworks have been conceived in order to support companies and their designers to develop sustainable products. In the circular economy, however, these frameworks no longer appear to be sufficient, due to the difficulty in identifying multiple design strategies for the different product life cycles across time dimensions. By adopting a Design for X (DfX) approach, this paper develops a multi-hierarchical DfX framework that allows designers to incorporate different strategies to better address product life cycles. This framework could facilitate the further development of a more comprehensive and interdisciplinary DfX tool. A key part of the method deployed is an interview guide approach, where five experts from across academia and industry, were interviewed. This qualitative research draws on their diverse expertise and generates an intersectoral link between different fields. Moreover, the DfX tool can be used to highlight relationships between different circular economy strategies, by providing insights into how interdisciplinary design decisions influence each other. Such an approach could allow designers to effectively visualize a bigger picture and positively influence the application and acceleration of the circular economy.

Introduction

Circular product design is a complex and interdisciplinary process. At the early design stages, a variety of designers must make decisions not only about the first lifespan of the product, but also forecasting where, when, for whom and how the product will be reintegrated in the following life cycles, as well as mitigate concomitant objectives in business, engineering, product and service design. Indeed, in contrast to today's linear economy, circular economy (CE) presupposes a constant resourcing cycle aimed at preserving natural assets, maximizing the use of natural capital and decreasing human impacts on nature (McDonough, et al., 2010; Stahel, 2010; Bakker, et al., 2014). This new vision implies a substantial change not only on the product design, but in the entire organizational system of our society. Hence, it is de facto unlikely that an optimal transition will occur if there is an imbalance between disciplines and the system could not be considered as a holistic, complex structure, to be designed and managed (Murray, et al., 2017).

The collaboration between so many fields has always been fundamental to respond to the exponential complexity of systemic thinking for sustainability. Some frameworks, such as Ecodesign Strategy Wheel (Brezet, H., & Van Hemel, C. 1998), Product-system lifecycle (Vezzoli, et al., 2008), Whole System Design (Charnley, 2010) are well known to take in consideration the bigger picture for sustainable and interdisciplinary decision-making. However, these frameworks tend to neglect the different design approaches for the different life cycles of the product, which are essential factors to consider in designing for the CE. For this reason, it is necessary to review these existing frameworks on which the design is often based today and reframe a new and up-to-date framework that also tackles multiple loops.

The first challenge to develop a comprehensive framework among so many variables is to determine a common terminology (Sauvé et al. 2016). Many researchers, published works, conferences and tools make use of the Design for X (DfX) approach to make designers aware about the implications of their design decisions on later life cycle phases of a product. In these activities, 'X' is used as a variable which represents a specific design strategy. Huang (1996), defined DfX as an "imperative practice in product development to achieve simultaneous improvements in products and processes". Many DfX approaches have also been addressed in the present CE literature (Bakker et al., 2014; Go, et al., 2015; Van

Weelden, et al., 2016, De los Rios, et al., 2017 and Moreno, et al., 2017). Therefore, the DfX can arguably be used to map a circular approach, to a sequence of detailed interdisciplinary strategies, acting as a flexible pattern to be applied according to the circular design requirements.

In this paper, through the theoretical application of DfXs, the authors present a framework by which it is possible to hierarchy circular strategies that cover the life cycle of products across temporal dimensions. Furthermore, this paper introduces how the framework could be used for the future development of an interactive and open-sourced design tool.

Methodology

To build robust bases capable of supporting the complexity, information volume, overlapping concepts and the wide scope of design disciplines, a methodology has been structured, in line with Friedman (2003) that comprises of four steps outlined below.

Friedman states that theoretical construction cannot be based on practice. Indeed, it is questionable how critical and systematic thinking can be established based on case studies, that meet specific contextual, productive and temporal requirements. Practice can, however, provide a validation of the questions that were created via theory (Friedman, 2003). Theory can be based on a general structure that can be revised, reformulated and reorganized, according to very precise logic, allowing one to develop a resilient theoretical framework (Webster, et al., 2002).

The research shown in this paper therefore used this theoretical framework consisting of four steps: (1) Discover - an exploratory review of the literature, after which a (2) Define - concept map was defined and developed (3) Develop - three initial hypothesis and finally (4) Validate - the hypothesis was validated through 5 guided interviews (Fig. 1). There are iteration loops from step 4 back to steps 1, 2 and 3. The structure deployed forms part of a larger ongoing PhD research activity and requires further steps in order to develop the final PhD work.

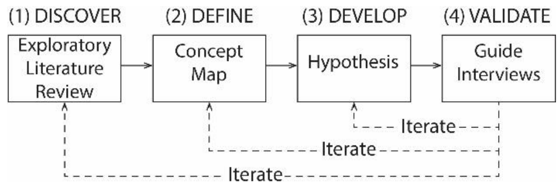

Figure 1. Methodological steps.

Discover - Exploratory Literature Review

To understand and define the main DfX strategies and try to create continuity between them in the various phases of the design process, it was decided to undertake a first research on the most common design practices with respect to the circular economy according to Webster, et al., (2002). The tool used for this research was Google Scholar, the keywords used in multiple combinations were "Design Theory", "Design Disciplines", "Circular Product Design", "Circular Economy", "Design Process", "Systemic Design ","Design for X", and "Design for Collaboration". All the terms were first searched individually and then combined using AND as a conjunction between the different keywords. Along with the material found through the review of the literature, some texts reputed fundamental were added (such as Brezet, et al., 1998, Vezzoli et al., 2008; Stahel, 2010 and Nasr, et al., 2018). All literature generated was considered.

Define - Concept Map

To group and view the findings of the exploratory literature review, the concept map methodology was used. This methodology allows the interdependencies of the different concepts to be connected through logical reasoning (Novak, et al., 2008). Because the goal of the research was to define an interdisciplinary framework, the concept map developed around the word "Design for Collaboration". Subsequently, to give importance to all the design phases, the word "Design for Collaboration" was connected with every single phase of the life cycle of the closed-cycle product readapted based on the frameworks of Brezet, et al. (1997), and Vezzoli, et al. (2008).

This step helped to connect the main influences of different design disciplines with each phase of the product life cycle. For some of the phases of the life process of the product a DfX was assigned in order to establish the possible disciplines which are able to deal with this design phase. The map presented in Fig. 2 does not intend to be a map that includes all the strategies identified, but only an analysis of key aspects.

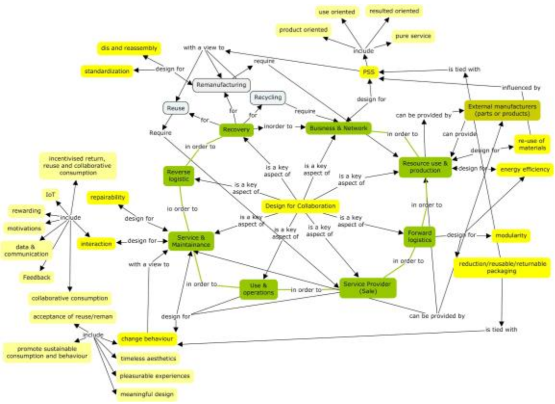

Figure 2. Concept map.

From Fig. 2, a series of observations can be made.

- Some DfXs can be applied by different disciplines / designers simultaneously (Kuo, et al., 2001)
- Some DfXs are applicable exclusively in specific disciplines / designers
- Some DfXs are the consequence of hierarchical decisions (Huang, 1996)
- Some DfXs are mutually non-exclusive
- Some DfXs are mutually exclusive
- Some DfXs are complementar (Van Weelden, et al., 2016; De los Rios, et al., 2017; Moreno, et al., 2017)
- Some DfXs are applicable across time dimensions
- Some DfXs follow different processes in different contexts and times
- Some DfXs are applicable in single and different phases
- Some DfXs can be applied consequently
- Some DfXs can be applied in parallel
- Some DfXs can take effect after the first loop of the product
- Some DfXs may progressively increase or decrease in effectiveness in different loops
- Several DfXs have variable effectiveness on different products

The synthetic DfXs list of observations highlight the complexity of the hierarchization. Consequently, it was hypothesized that a hierarchy of DfXs should follow a multi-hierarchical approach. While a detailed verification of the entire conceptualization presented in Fig. 2 goes beyond the scope of this study, this has been useful to formulate three hypotheses which are the interpretation that resulted from it.

Develop - Hypothesis

Three distinct hierarchies for DfX are conceivable. The first hypothesis relates to the hierarchy of the priority orders of the 'X' strategies. For example, with a view to implement a design strategy for refurbishing (X^1) it is essential, in sequential order, work on design for disassembly (X^2) and then more in detail on design for maintenance (X^3), etc. (Van den Berg, et al., 2015), respectively X^1, X^2, X^3. 'X' may vary in detail in the applied design strategy. The X^1 determines the main circular strategy or in other words Maintenance, Reuse, Redistribute, Refurbish, Remanufacture, and Recycle, whereas X^2, X^3 the possible design strategies to reach X^1. Hence, the first hypothesis is:

H1

To achieve the first degree DfX (X^1) a hyperbolic tree hierarchy diagram, that describes each sub DfX strategy, can be used (Fig. 3).

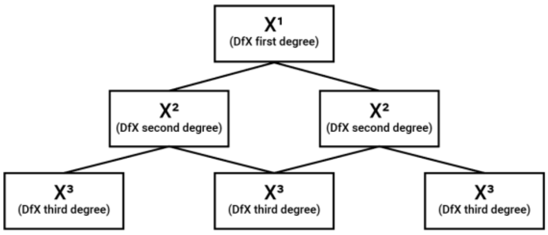

Figure 3. DfX hierarchization based on degrees of priority and design specifications.

Companies organize product development based on the phases of product lifecycle. The choices made during each phase (P) of the process can influence the subsequent phases (Cataldo et al., 2006). In order to achieve X^1, a variety of designers, in different design phases, should coordinate their own DfXs effectively using specific X^2 and X^3. Hence, the second hypothesis is:

H2
Through a circular life cycle phase diagram, it is possible to position any DfX for each phase (Fig. 4).

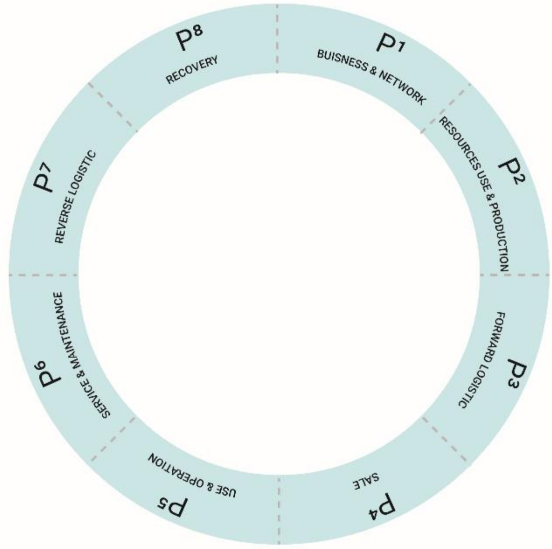

Figure 4. DfX hierarchization based on the phases of the product life cycle.

CE aims at recovering products for many loops by using as less energy and materials as possible for each loop (Bakker et al. 2014). In business terms, the life cycle of the product should last for many loops (L) by using specific combinations of strategies in order to make the business last longer. With that aim, designers should foresee which X^1 should be applied for each product lifetime (L^1, L^2, L^3, etc.) in order to then decide in a hierarchical configuration X^2 and X^3. Hence, the third hypothesis is:

H3
In a spiral loop diagram, DfXs can be applied over multiple product life cycles (Fig. 5).

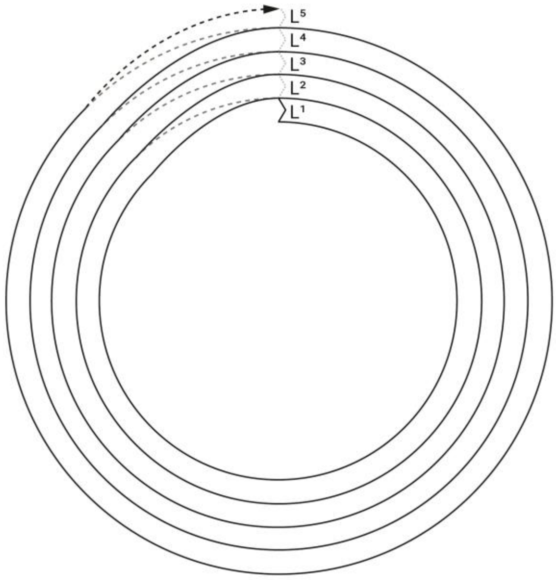

Figure 5. DfX hierarchization based on the different loops / temporal dimensions.

Validate - Interview guide
In the last step of the methodology, an interview with experts from the academic and industrial world through a guided face-to-face interview was undertaken. This methodology consists of asking all the interviewees the same questions, leaving them free to explore specific issues (Patton, 2002) to validate the proposal. A brief description of the profiles and skills of the interviewees has been provided in Tab. 1.

No.	Area of CE expertise	Sector	From
1	User experience and product design	Acade.	USA
2	Transportation and mobility systems	Acade.	USA
3	Consumer electronics, nanomaterials, and lithium-ion batteries	Acade.	USA
4	Policies supporting energy technology, energy systems and information technology	Acade.	USA
5	Product lifecycle design and remanufacturing	Indu.	USA

Table 1. Specification on the competences and origin of the interviewees.

Framework validation

Respondents were informed of the methodological process described above. First, the interviewees were asked whether they found the three hypotheses, Fig. 3, 4, and 5 interdependent and whether a simultaneous use of these hierarchies would have favored an interdisciplinary decision-making on multiple temporal dimension. Subsequently, the specific requirements of the hierarchization of the three dimensions and the potential of a possible tool on the basis of hierarchization were examined. The areas considered in this phase included the requirements related to the application of different strategies in terms of application, relations and management of the different DfXs by different designers. The interviews provided valuable information on the possible hierarchy of DfX, validating all the processes which led to formulate the final framework (Fig. 6). Some key comments can be summarized in two categories, multi-hierarchies and use of the future tool.

Multi-hierarchies' considerations:

- The choices made in L^1, P^1 influence all the remaining choices;
- The design process always begins with L^1, P^1 but may not proceed in sequential order;
- X^1 is the only objective of each phase (P) and each loop (L);
- X^1 varies with the variation of Ls;
- X^1 should be the only target, while X^2 and X^3 may vary in both number and importance depending on the product;
- The common denominator from which to select the DfXs is the cost, to then refine the selection of subsequent strategies;
- X^2 represents the specific strategy for each phase;
- The hierarchy of contents should be standardized to the various disciplines and easily integrated within different companies;
- The choices of the DfXs is influenced also for each loop by external factors such as politics, technology, society, and culture;

Considerations for the future tool for the future tool:

- The tool must be able to simplify the vision but at the same time to maintain a scientific rigor;
- The tool should help to manage the overhead of designing alternatives by defining basic objectives to focus on;
- The tool should help the designer to establish the priorities of the different DfXs in a dynamic and intuitive way;
- To facilitate control by system designers, there must be a mechanism capable of showing quantifiable information flow for prioritizing different DfXs;
- Through case studies, it is possible to facilitate an immediate understanding of the strategy applied in reference;
- The hierarchy is not only direct but also indirect between the different disciplines, so the relationships between different DfXs should be emphasized jointly;
- Different companies could have variable departments and structures and not have complete control of the design process, the tool should be able to be used cross-companies;
- Companies may be able to tailor their approach to different needs;

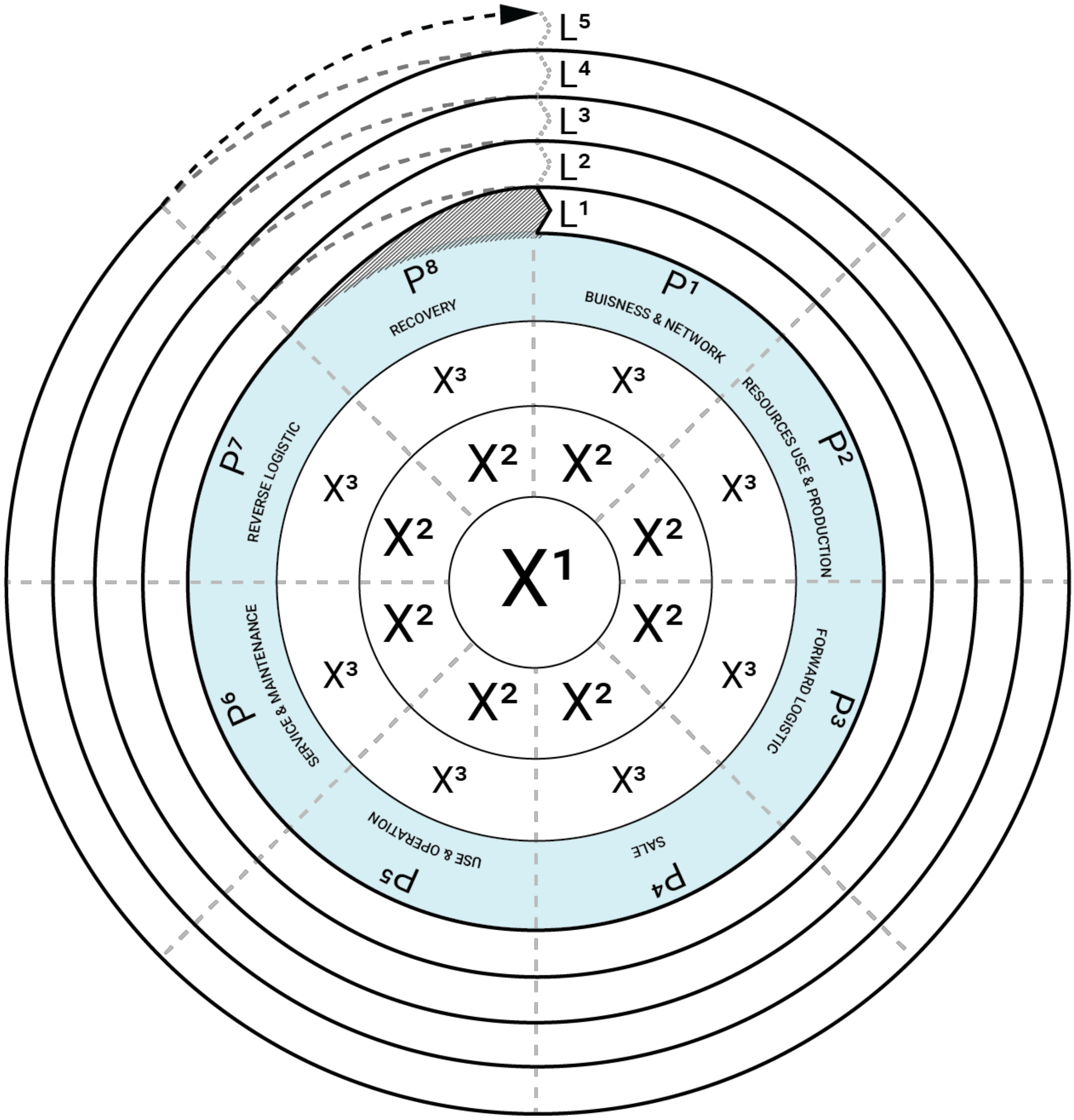

Figure 6. Multi-hierarchical DfX framework.

Circular Design Tool: future development and concluding remarks

In a circular context, the good organization of the different DfX strategies is the key to increase profitability across multiple loops. This paper presents a *Multi-hierarchical DfX Framework* that will shape the basis of an interdisciplinary tool. The tool will help designers to identify for each loop (L) a circular objective, defined here as a X^1 strategy, which might be maintenance, reuse, redistribute, refurbish, remanufacture, or recycle. All appropriate DfX strategies to pursue directly the achievement of the X^1 can be considered X^2 strategies. The same principle applies to the X^3, X^4 and so on. When designing for a new loop, the X^1 strategy may change. If so, X^2 and X^3 strategies may change accordingly. Different designers (e.g. business, engineers, product or service designers) should be able to set an appropriate combination of X^2, X^3 in order to achieve X^1.

Through this tool, designers will be able to dynamically compare and identify DfX strategies from the early stages of the design process. In order to make the management of the complexity easier, the tool can suggest correlated DfXs based on the X^1 identification for each loop (Fig. 7). This could help designers in coordinating relations between design strategies for three reasons; the first reason is to manage the interdependences between different strategies. For example, if the designer decides that X^1 in the L^1 is Design for Refurbishing, in L^2 P^4 a consequential logical X^2 is Design for Change Behavior and X^3 could be Design for Consumer Acceptance of Refurbished Product (Pazhani, et al., 2014; Van Weelden, et al., 2016). The second reason is to exclude the strategies that conflict one another. For example, if the designer decides that X^1 in the L^1 is Design for Recycling, in L^2 P^5 the X^2 cannot be Design for Attachment and Trust. The third and last reason is to help monitoring and forecasting crucial DfX strategies. For example, if the designer decided that from L^1 to L^4, X^1 is Design for Remanufacturing, the designer should define if X^2 in P^8 is Design for Closed Loop Supply Chain Networks, or instead Design for Open Loop Supply Chain Networks (Ene, et al., 2014). These decisions could completely change consequential strategies in the other loops.

This research is a step forward to the mastery of the circular design strategies. More research is needed to collect and map DfXs according to the multi-hierarchical framework presented in this paper. A first prototype of the tool was developed and made available at www.circulardesign.it.

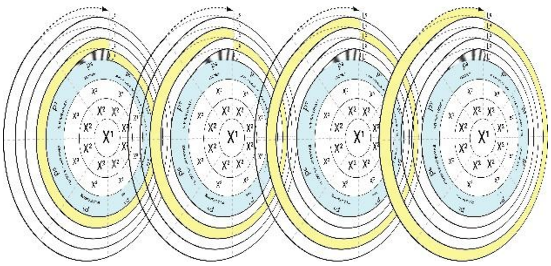

Figure 7. Visualization of the initial decision-making process of X^1 related to each loop.

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