Journal of Business Venturing Design 4 (2025) 100028

Contents lists available at ScienceDirect

Journal of Business Venturing Design

journal homepage: www.elsevier.com/locate/jbvd

Circular Systems Sandbox: A process tool for circular systems design and rebound effect reduction

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ARTICLE INFO

Keywords:
Circular economy
Rebound effects
Systems
Business model
Design science
Tool

ABSTRACT

This paper develops and validates a novel design artifact called Circular Systems Sandbox. While there is an abundance of literature on new product development and business model innovation, a notable gap exists in integrating these two domains. More systemic design is deemed indispensable because the mismatched design of products, services, business models and collaborations lead to harmful rebound effects. We employ a mixed methods design science approach involving 31 expert interviews, 11 workshops, and an experimental evaluation with 108 participants. The findings demonstrate that the Circular Systems Sandbox significantly enhances the quality of circular product and business model design, providing a practical and comprehensive framework for entrepreneurs. The study contributes to theory by elucidating the interconnections within Circular Systems Design, offering preventive strategies for rebound effects, and aligning with calls for systemic solutions for the Circular Economy. This paper not only advances Circular Systems Design as a concept but also empirically proves its utility, encouraging future research and application in diverse sectors.

1. Introduction

The circular economy (CE) is increasingly advocated as an essential economic paradigm shift aimed at preservation and regeneration (Kirchherr et al., 2023). Sustainable entrepreneurs are recognized as trailblazers in this transformation, capable of implementing more radical solutions than established firms (Bauwens et al., 2019; Suchek et al., 2022). By creating innovative circular products and circular business models from scratch, entrepreneurs can offer efficient and coordinated solutions to environmental problems (Blomsma et al., 2023; Dean & McMullen, 2007). However, how entrepreneurs design circular products and business models in parallel, given their complete freedom of design, remains largely unknown.

The theoretical relevance can be illustrated using the case of e-scooters, which numerous ventures attempted to offer as a sustainable alternative to inner-city car trips. When they were first implemented, e-scooters frequently broke down because they were not designed to withstand heavy use by inexperienced riders and were difficult to repair. Additionally, they exacerbated street congestion due to inadequate recharging partnerships and the absence of designated parking zones, making them an unsustainable inconvenience (Schellong et al., 2019). The public referendum banning e-scooters in Paris highlights the repercussions of disjointed circular design (Nouvian, 2023), where product design does not align with a sharing business model (Geissdoerfer et al., 2020), and which fails to secure essential support from stakeholders for parking and charging.

This example underscores the necessity for more harmonious and systemic circular design, as advocated by several scholars (Baldassarre et al., 2020; Velenturf & Purnell, 2021; Wiprachtiger et al., 2020). Circular Systems Design (CSD) encompasses the concurrent design of products, services, business models, and stakeholder collaborations for circular value creation (Remke & Müller, 2024). This integrative design approach has been described as a critical method to reduce circular economy rebound (CER) (Siderius & Poldner, 2021; Zink & Geyer, 2017). CER manifests when circular products stimulate additional production and consumption instead of substituting existing products, either due to their inability to compete with linear products in terms of quality and price, or through intensified use and wear driven by their perceived environmental benefits, as observed with sustainable packaging or e-scooters (Castro et al., 2022; Figge & Thorpe, 2019). CSD holds the promise of achieving price and quality parity while keeping production and consumption in a sustainable balance (Metic & Pigosso,

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https://doi.org/10.1016/j.jbvd.2025.100028
Received 30 June 2024; Received in revised form 31 January 2025; Accepted 18 March 2025
Available online 25 March 2025
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2022). However, there remains a lack of understanding regarding both the fundamental components of CSD and its mechanisms for preventing CER. This study aims to equip circular entrepreneurs with a comprehensive tool for holistic CSD that proactively addresses CER. Thus, we aim to answer the following research question: *How can circular entrepreneurs harmonize the design of products, services, business models and collaborations to create sustainable circular systems?*

We draw on design science research (DSR) methodology for developing design artifacts (Baskerville et al., 2018), following the research cycle outlined by Dimov et al. (2023). We first justify the need for such an artifact by grounding it in a thorough review of the literature and examining a total of 85 design artifacts from both theory and practice. We then develop a preliminary blueprint of the artifact using an inductive empirical research design, involving 31 semi-structured interviews with circular design experts and entrepreneurs. The resulting blueprint is evaluated through 11 workshops with additional circular design experts and entrepreneurs, collecting their feedback and illustrative quotes to adapt the artifact accordingly. This process culminates in a comprehensive design tool, which we term the Circular Systems Sandbox. To assess the tool's efficacy in facilitating CSD and reducing CER, we employ an experimental research design (Lonati et al., 2018). The experiment was structured as an eight-week design challenge engaging 108 participants, resulting in 15 project submissions that were evaluated by an expert jury using structured assessment criteria. Results indicate that the Circular Systems Sandbox leads to superior design outcomes and lower CER compared to existing tools.

The present study makes three significant contributions. First, we connect the isolated literature streams on circular product design (CPD), product-service system (PSS) design, circular business model (CBM) design, and collaborative ecosystem design, illustrating the interactions within CSD and how to navigate between these design levels. Second, we explain how CSD can effectively reduce CER as a preventive design measure. Third, the heart of this study – the Circular Systems Sandbox – incorporates insights and lessons from experienced circular entrepreneurs and designers, providing future generations of entrepreneurs and researchers with a comprehensive framework for establishing circular systems and accelerating the sustainability transition.

2. Conceptual background

The creation of our artifact is inspired by a thorough review of various circular design concepts. Overall, we posit that CSD follows the logic inherent to the CE, which is defined as "a regenerative economic system which […] replaces the 'end of life' concept with reducing, reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development […], enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities" (Kirchherr et al., 2023, p. 7).

2.1. Circular design

Circular design can be categorized into four interlinked and nested levels (Baldassarre et al., 2020): (1) CPD is an integral part of (2) PSS design, which is embedded within (3) CBM design, which subsides in (4) collaborative ecosystem design to realize circular value creation. The simultaneous consideration and harmonization of these interlinked design levels constitutes CSD (Remke & Müller, 2024). Integrating these domains is deemed indispensable not only for practical implementation but also for advancing sustainable design theory (Baldassarre et al., 2020; Ceschin & Gaziulusoy, 2016; den Hollander et al., 2017; Iacovidou et al., 2021).

2.1.1. Circular product design

CPD encompasses strategies aimed at preserving a product's functionality and physical integrity, utilizing materials and components across multiple lifecycles, and maintaining its overall value (Diaz et al., 2022; Moreno et al., 2016; Wang et al., 2022). Existing research primarily focuses on "Design for X" guidelines, where the "X" denotes a specific attribute such as repairability or recyclability (Franconi et al., 2022; Sassanelli et al., 2020). Den Hollander et al. (2017) emphasize the importance of maintaining product integrity by extending lifespans, preventing obsolescence, and ensuring effective recovery. Mesa et al. (2019) advocate for an open product architecture, emphasizing modularity, standardization, and reconfiguration. Product designers are also advised to differentiate between biological and technical materials (McDonough & Braungart, 2010; Mestre & Cooper, 2017). Furthermore, CPD involves considering non-technical factors such as aesthetics and emotional attachment (Chapman, 2009).

2.1.2. Product-service system and circular business model design

Implementing circular products requires the exploration of innovative PSS and CBMs to facilitate their seamless delivery (Franco, 2019; Moro et al., 2022). Consequently, circular products evolve from mere physical entities into complex value-delivery systems (Diaz et al., 2022; Vezzoli et al., 2017). Offering circular products entails clearly defined responsibilities, which businesses address through the development of comprehensive PSSs. These PSSs extend simple product delivery by adding circular strategies such as repair and maintenance, upgrades, take-back, and recycling (Tukker, 2015). By expanding value creation and delivery activities towards circularity, the development of corresponding value capture mechanisms results in the formation of CBMs (Geissdoerfer et al., 2020). Here, the same product can now be monetized multiple times, often in various ways. Firms frequently generate more revenue in later product life cycles, as resources have been amortized several times, creating new revenue streams but also adding complexity in management and accounting (Fallahi et al., 2023).

2.1.3. Collaborative ecosystem design

The successful implementation of CBMs is primarily facilitated by effectively designed collaborations and value exchanges between stakeholders in the ecosystem (Kanda et al., 2021; Pieroni et al., 2019; Trevisan et al., 2022). Brown et al. (2021) highlight that ecosystem experimentation and collaboration represent a decisive success factor for the functioning of CBMs. The complexity of the CE requires designers to have expertise in a wide array of fields including economics, ecology, supply chain and stakeholder management (Borms et al., 2023; Dokter et al., 2021). Therefore, a more granular aspect of collaborative ecosystem design is the formation of complementary and multidisciplinary teams (Brown et al., 2021; Cuomo, 2022; Wang et al., 2022).

2.2. Rebound effects

The alleged potential of CSD is the ability to substantially reduce negative externalities such as CER (Castro et al., 2022). Originally described for energy economics (Greening et al., 2000), scholars have asserted that rebound effects also subside circular practices (Figge & Thorpe, 2019; Metic & Pigosso, 2022; Zink & Geyer, 2017). CER occurs when positive environmental impact achieved through sustainable production and consumption is negated by a simultaneous increase in production and consumption levels (Zink & Geyer, 2017). For instance, the positive perception of recycled coffee cups might encourage consumers to use them more frequently, inadvertently diminishing the initial environmental benefits. Moreover, when circular products fail to compete with linear products in price and quality, they often cater only to environmentally conscious niche markets, leading to additional production and consumption rather than substitution (Zink & Geyer, 2017). Castro et al. (2022) further argue that circular activities often require novel infrastructure and substantial energy (e.g., recycling), which can offset initial benefits. The challenge is that CER is usually identified retrospectively, missing consideration in the design phase (Das et al., 2023; Zerbino, 2022). While Niero et al. (2021) suggest that conducting

Life Cycle Assessment (LCA) is not sufficient to avoid unintended side effects of CE initiatives, Siderius and Poldner (2021) argue that a systems thinking approach fostering the intelligent construction of circular systems holds strong potential to mitigate CER. Besides early detection through systemic approaches, CER can be mitigated by educating and empowering the population, gamification and penalization, environmental policy, and price control (Castro et al., 2022; Das et al., 2023; Zerbino, 2022).

2.3. Review of circular design tools

To ensure our artifact creation is relevant and rigorous, we reviewed 85 existing generative circular design tools (de Koeijer et al., 2017). The tools were identified through a systematic keyword search on Web of Science, Google Scholar, and Google, using combinations of terms such as 'circular,' 'design,' 'tool,' 'model,' 'framework,' 'system,' and 'business model.' This search yielded 28 tools from academic research and 57 tools from practice. The tools were categorized based on their type, design level, and whether they are process-based. We excluded industry-specific tools to ensure a cohesive and universally applicable selection adaptable to various contexts, resulting in a final selection of 65 tools from both theory and practice (Appendix A). The tool review highlights a significant gap, evidenced by the absence of tools addressing a systemic approach, which we define as connecting three or more design levels (0 %). Additionally, we identify a lack of tools offering a clear design process with steps and iterations (27.69 %). Circular design demands iterative testing with stakeholders under real-world conditions (Brown et al., 2021), a requirement not fully addressed by contemporary tools.

3. Method

We employ DSR to support entrepreneurs with practical tools for the sustainability transition while theorizing CSD and its role in reducing CER (Romme & Holmström, 2023). Following the DSR cycle by Dimov et al. (2023), we start by outlining a practical problem and research need (justifying), create a design artifact to address the identified problem (creating), evaluate its effectiveness in solving the issue (evaluating), and theorize its mechanisms (theorizing). The artifact development proceeded through two iterative cycles of creation and evaluation (March & Smith, 1995), with evaluation findings informing the refinement of our artifact. Fig. 1 illustrates the DSR process of the present study.

3.1. Problem definition and solution objectives

We observe two distinct problems: (1) an insufficient understanding of CSD and CER in the literature and (2) a lack of holistic and processual guidance for entrepreneurs and practitioners in realizing circular value creation (Baldassarre et al., 2020; Kalmykova et al., 2018; Royo et al., 2023). The objective of the artifact is to facilitate the integrated design of circular products, services, business models, and collaborations. Creating and evaluating the artifact in collaboration with experienced circular designers and entrepreneurs will help uncover how the CSD process unfolds in practice, the mechanisms and dependencies between design levels and how optimizing these decisions can reduce CER. The final artifact aims to simplify the design process, produce more refined circular systems, and reduce CER.

3.2. Artifact design and development

The artifact development integrated best practices from existing tools with empirical insights derived from circular design experts and entrepreneurs (Baskerville et al., 2018). Our data collection comprised 31 semi-structured interviews, each approximately 60 min in duration (Table 1). Thematically, we were interested in understanding the CSD process, highlighting challenges, inherent trade-offs and interdependencies between design levels. Interviews were transcribed and subsequently analyzed using axial coding techniques (Gioia et al., 2013; Strauss & Corbin, 1998). In the first step, we generated in-vivo codes that captured granular and nuanced insights into the CSD process. These first-order codes were then systematically aggregated into 27 s-order themes through an iterative process of comparison and theoretical integration. Emerging codes were discussed bilaterally between researchers to ensure coding reliability (Campbell et al., 2013). Further abstraction yielded five third-order dimensions that represent the fundamental process phases of CSD (Fig. 2). From this analytical foundation, we developed the initial artifact through systematically arranging and connecting the second-order themes into a process blueprint that captured the CSD patterns described across interviews. For instance, system research has consistently been named as the foundational phase in the CSD process. The resulting artifact, incorporating both sequential dependencies and iterative elements, served as the foundation for subsequent demonstration and evaluation (Dimov et al., 2023; Venable et al., 2016).

3.3. Artifact demonstration and evaluation

3.3.1. Artifact workshops

To assess and refine the artifact, we conducted a series of structured evaluation workshops with circular design experts and entrepreneurs. The evaluation phase comprised 11 workshops between December 2023 and March 2024, each around 50 min in duration. The participant pool integrated both previously interviewed experts and newly recruited participants (Table 2). This methodological approach integrated two complementary angles. First, we gained insights from unbiased experts who provided fresh interpretations of the artifact, and second, verification from previous participants who could assess whether their experiential knowledge had been accurately captured and represented by our artifact.

To facilitate the workshops, we placed the artifact within the digital collaboration platform Miro and recorded the sessions via Zoom. During the workshops, we walked participants through the process blueprint, explained the interactions, and addressed any arising questions or comments. Where applicable, we used the illustrative case of e-scooters to demonstrate practical application. The tool was collaboratively refined by adding post-its with feedback to the different sections of the blueprint. The evaluation process yielded predominantly positive responses, with illustrative quotations extracted from workshop transcripts to substantiate and guide subsequent artifact refinements (see Appendix C). We continued this form of workshop until we primarily received comprehension questions, indicating a more mature and refined state of the artifact. This iterative development culminated in the "Circular Systems Sandbox," an interactive framework enabling entrepreneurs to configure and refine circular systems within a flexible digital environment. The final artifact incorporates several key enhancements that emerged from the workshops. First, we enhanced clarity through detailed descriptions of the process steps, providing users with comprehensive methodological guidance. Second, we integrated dedicated ideation and working spaces to facilitate exploration and iterative refinement. And third, we added our first-level codes as a knowledge repository at the bottom of the artifact, providing users with contextual insights and empirical examples to support and inspire their design decisions. This refined tool architecture supports systematic experimentation with CSD configurations, enabling practitioners to develop economically viable and environmentally sustainable circular systems.

3.3.2. Experiment

After refining the artifact, we evaluated its effectiveness by

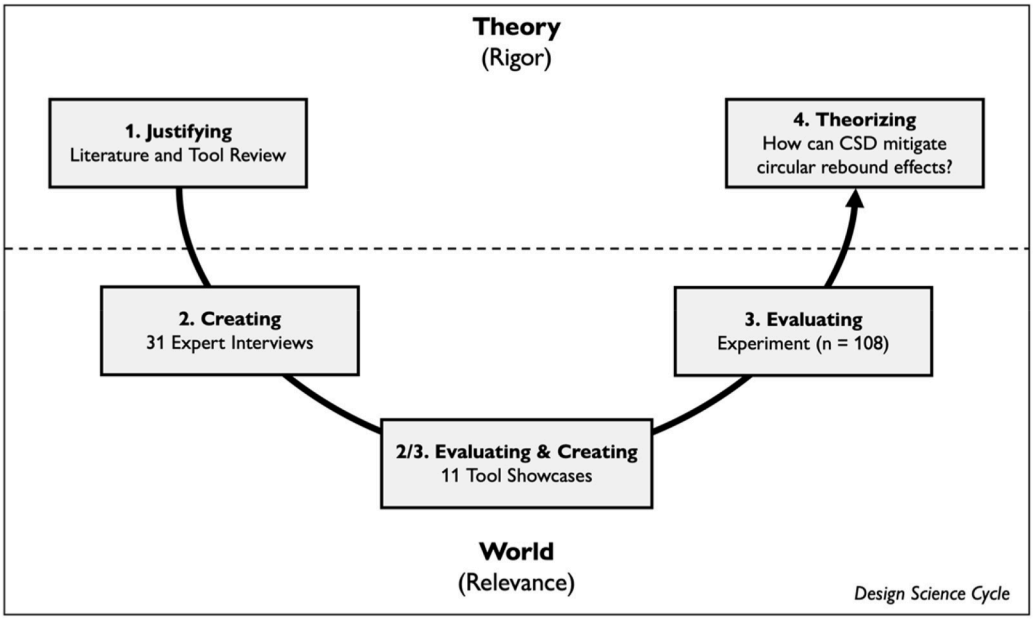


Fig. 1. Design science cycle of this study.

conducting a randomized controlled trial[1] (Lonati et al., 2018). The aim was to assess whether the *Circular Systems Sandbox* performs better at designing circular systems compared to existing tools.

3.3.2.1. Experimental design. To conduct the experiment, we partnered with an international design academy to create a free eight-week design challenge focused on the circular economy and systemic design. We promoted the challenge through LinkedIn and paid Instagram ads. The central design task required participants to design a circular system capable of displacing an existing and unsustainable linear solution. The experiment used a structured e-learning environment that guided participants through the CSD process with curated videos, articles and case studies. The treatment group received exclusive access to the *Circular Systems Sandbox* along with five instructional videos, totaling one hour (Fig. 3). To ensure methodological rigor, we constructed an active control group which we guided to other high-quality tools that we identified in our review. We aligned our recommended tools with the specific CSD phases: System Research (System Mapping Worksheets[2]), Life Cycle Thinking and System Creation (Circular Design Guide,[3] Circular Rebound Tool,[4] Design for X Tool[5]), System Fit (Circular Material Library[6]), System Evaluation (Circularity Assessment Tool,[7] Idemat LightLCA App[8]). Communication with participants was maintained via email and two separate Discord servers to avoid experimental contamination. Both groups received identical support, including half-time consultation sessions and regular masterclasses featuring circular entrepreneurs discussing their CSD approaches. To maintain experimental control, the research team took a passive role and deliberately constrained their communication to short and professional replies related to challenge logistics, denying individual feedback. Other project-related notifications were always sent out in parallel. Design evaluation criteria were established in a design brief at the start of the challenge. To ensure fairness, we offered two equivalent awards. Each group's winning submission was admitted to an incubation program and received membership in a sustainable entrepreneurship collective with access to offices and makerspaces to continue working on their startup project.

At the conclusion of the challenge, we evaluated the project submissions using comprehensive judging rubrics that integrated entrepreneurial and ecological dimensions. Several complementary categories were chosen to form a systematic evaluation framework. The evaluation framework comprised eight equally weighted categories, each assessed on a 10-point scale: design completeness, innovativeness, approach/methodology, impact potential, resource efficiency, scalability, business model viability/feasibility, and rebound effects. For instance, impact potential examined clear linkages to ecologic outcomes, while scalability considered the go-to-market strategy and adoption feasibility. This balanced evaluation structure was deliberately chosen to provide a balanced and comprehensive assessment of the artifact and to evaluate its strengths and weaknesses across different dimensions. For instance, while we expect stronger performance in rebound effect reduction, existing tools may demonstrate comparable or superior performance in areas such as impact potential or innovativeness. To ensure evaluation reliability, we developed detailed scoring guidelines with explicit point-range criteria to offer judges more guidance and precision in awarding points (see Appendix B). Submissions were first anonymized and then individually blind reviewed by four judges who had no prior knowledge of the content of participants' projects. Although all four judges helped organize the competition and had access to the course platform, communication was strictly limited to challenge logistics to maintain blinding and ensure a fair competition for all participants. The jury comprised two experienced designers from the design academy and two researchers from our research team to combine sentiments from practice and academia. To ensure that evaluations are reliable, we calculated the inter-rater reliability using the Kendall coefficient of concordance, selected for its suitability with ordinal data and multiple raters (Gisev et al., 2013). The analysis showed substantial inter-rater agreement between judges ($W = 0.779$, $p < 0.001$), meeting established reliability thresholds (Gisev et al., 2013; Landis & Koch, 1977). This indicates that evaluations of CSD quality were consistent between research and practitioner teams.

Finally, we conducted an exit survey ($n = 22$) to learn about

[1] The experiment was pre-registered at https://aspredicted.org/R9P_2PL
[2] https://www.systemsinnovation.network/discovery
[3] https://www.ellenmacarthurfoundation.org/circular-design-guide/overview
[4] Das et al. (2023)
[5] https://www.circulardesign.it
[6] https://circularmateriallibrary.org
[7] https://circitnord.com/tools/circularity-assessment-tool/
[8] https://idematapp.com/coll-page-section/lightlca/

Table 1
Interview participants.

#	Industry Sector	Job Description	Firm Size	Design Expertise	Origin
1	Textile Manufacturing	Product Designer – Sustainable Design & Strategy	Startup	16 years	Germany
2	Design Services & Education	Founder & Chief Product Officer	Startup	12 years	Germany
3	University	Ph.D. Researcher Industrial Design Engineering	Large	11 years	Netherlands
4	Research	Co-Head Circular Transitions	Large	7 years	Germany
5	Textile Manufacturing	Development Manager Sustainable Materials	Medium	5 years	Switzerland
6	Design Services & Education	Circular Material Researcher	Small	3 years	India
7	Energy Services	IoT Requirements Engineer	Large	13 years	Germany
8	Retail	Manager for Circular Material Innovations	Large	11 years	Canada
9	Textile Manufacturing	Circular and Sustainable Material Expert	Large	36 years	Switzerland
10	Design Services	Director for Material & Circular Product	Medium	31 years	Norway
11	Environmental Services	Project Manager Circular Economy & Ecodesign	Small	5 years	Germany
12	Design Services	Director & Owner Bio-based Design Startups	Startup	18 years	Netherlands
13	Design Consultancy	CEO & Founder of Design Consultancy	Startup	27 years	Germany
14	Construction	Project Manager Circular Economy & Sustainability	Large	4 years	Switzerland
15	Design Services	Co-Founder & CEO of Circular Startups, Materials & Circular Economy Expert	Startup	27 years	Germany
16	University	Strategic Designer, Research Associate & Consultant in Circular Product Design	Medium	10 years	Germany
17	Design Services	Co-Founder & Chief Product Officer	Startup	37 years	UK
18	Design Consultancy	Partner Regeneration & Circular Economy	Small	8 years	Turkey
19	Construction	Project Manager	Startup	10 years	Netherlands
20	Research & Education	Product Designer & Owner of Circular Design Studio	Medium	15 years	Netherlands
21	NGO	Strategic Design Manager	Medium	9 years	Denmark
22	IT Consultancy	Management Team & PhD Candidate	Small	9 years	Spain
23	Software Development	Co-Founder & Head of Product	Startup	7 years	Indonesia
24	Design Consultancy	Chief Designer Strategic & Circular Design	Small	30 years	Finland
25	Design Services	Independent Circular Design Consultant	Small	21 years	Netherlands
26	Environmental Services	Co-founder and CEO of Circular Startup	Startup	10 years	UK
27	Textile Manufacturing	Co-Founder of Circular Startup	Startup	11 years	Switzerland
28	Design Services	Research Fellow in Circular Design	Small	14 years	UK
29	University	Independent Consultant & Researcher on Circular Design	Large	39 years	Netherlands
30	Textile Manufacturing	Founder & Creative Director	Startup	17 years	France
31	NGO	Business & Policy Specialist for Circular Business Incubation	Medium	2 years	Netherlands

participants' project completion and their opinion of the artifact. The exit survey utilized 7-point Likert scales to assess the artifact's usefulness and ease of use (Davis, 1989). Both treatment and control groups evaluated their respective tools using identical criteria, supplemented by open-ended feedback opportunities.

3.3.3.2. Sample and randomization. Before beginning the challenge, we asked participants to fill out an entry survey and requested their permission to use their data for research purposes. In other words, they were aware that they were participating in an activity where we offered a free course in exchange for monitoring their actions for educational and research purposes. From 108 initial registrations, we collected information on their age, gender, job status, educational background, work experience, entrepreneurial experience, circular design experience, and expected level of commitment. We also grouped individuals in advance who indicated they were joining as a team. Random assignment divided participants equally between treatment and control groups ($n = 54$ each). We conducted randomization checks to ensure no significant differences existed between the groups. Table 3 shows that no significant differences existed between groups across any measured variables, confirming sample robustness.

The participant cohort was predominantly non-male (mean age = 30), with balanced representation across employment status (full-time workers, students, jobseekers) and educational backgrounds (business, design, sustainability). Most participants held university degrees with 3–5 years of work experience.40 % reported prior entrepreneurial experience while 30 % had basic or intermediate circular design knowledge. As expected with a free online challenge, participation declined over the eight-week period, which we monitored through Zoom session attendance. Although these numbers may not represent the total number of active participants, they provide a good indication (Fig. 4). Of

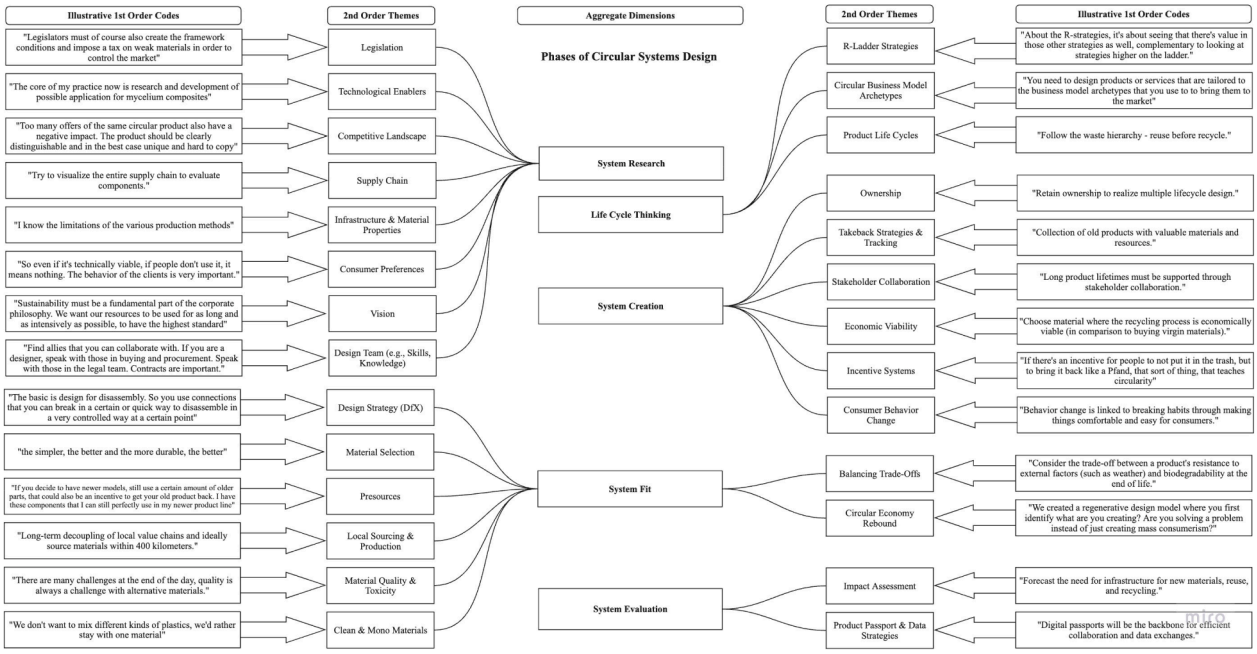


Fig. 2. Data structure.

Table 2
Workshop participants – Second round of creation and evaluation.

Interviewee	Participation	Industry Sector	Job Description	Firm Size	Design Expertise	Origin
1	2nd time	Design Services & Education	Founder & Chief Product Officer	Startup	12 years	Germany
2	2nd time	Design Services & Education	Founder	Startup	7 years	USA
3	2nd time	Research & Education	Product Designer & Owner of Circular Design Studio	Medium	15 years	Netherlands
4	2nd time	Textile Manufacturing	Circular and Sustainable Material Expert	Large	36 years	Switzerland
5	1st time	Textile Manufacturing	Circular Product Designer	Startup	14 years	Netherlands
6	2nd time	Academia	Strategic Designer, Research Associate & Consultant in Circular Product Design	Medium	10 years	Germany
7	2nd time	Design Services	Research Fellow in Circular Design	Small	14 years	UK
8	2nd time	Industry Platform	Strategic Design Manager	Medium	9 years	Denmark
9	1st time	Mobility	Senior Product Designer	Startup	8 years	Germany
10	2nd time	Academia	Ph.D. Researcher Industrial Design Engineering	Large	11 years	Netherlands
11	1st time	Academia	Project Manager & Ph.D. Candidate	Large	7 years	Germany

the 108 initial registrations, 15 projects were completed (14 %).

3.3.3.3. Data analysis. The four judges independently blind-reviewed the 15 anonymized project submissions using the standardized judging rubrics (Appendix B). We calculated average scores per rubric and summed them to determine the two winning submissions. We analyzed the differences in evaluation results using the Mann-Whitney U test. This non-parametric rank-sum test offers several advantages for this type of analysis (Siegel, 1957). First, it does not require the assumption that project scores are normally distributed. Second, our project scores are ordinal data, where the relative ranking is more meaningful than the exact numerical differences between scores. And third, parametric tests often require larger sample sizes for reliable results, whereas the Mann-Whitney U test is well-suited for smaller sample sizes (Wilcox, 2012), such as in this setting with a demanding multiple-week challenge. Thereby, we ensure a more accurate and reliable analysis of the project submissions, leading to valid conclusions about the performance and quality of the artifact. We complemented the main analysis with *t*-tests to analyze participant retention (comparing initial versus completing participants) and participants' tool evaluations from the exit survey.

4. Results

The iterative nature of the DSR cycle resulted in multiple findings that were repeatedly integrated into the final design of the artifact. Accordingly, the results draw on multiple rounds of creation and evaluation, which are presented in chronological order.

4.1. First round of creation & development

The first round of creation and development utilized empirical data collected through expert interviews and further drew inspiration from several frameworks on circular product and business model design (Bocken et al., 2016; den Hollander et al., 2017; Diaz et al., 2022; Franconi et al., 2022; Geissdoerfer et al., 2020; Lüdeke-Freund et al., 2019; Luttropp & Lagerstedt, 2006; Pieroni et al., 2020). Recognizing the utility of existing design knowledge at the different design levels, our objective was to integrate these perspectives into a comprehensive CSD process that harmonizes design decisions across them. This integrated approach builds on prior research while creating new synergies, contributing to both theoretical understanding and practical application in the field of circular design (Gregor & Hevner, 2013). The artifact was initially conceived as a process blueprint for CSD and served as the foundation for developing an advanced tool to support entrepreneurs in creating circular systems (Fig. 5).

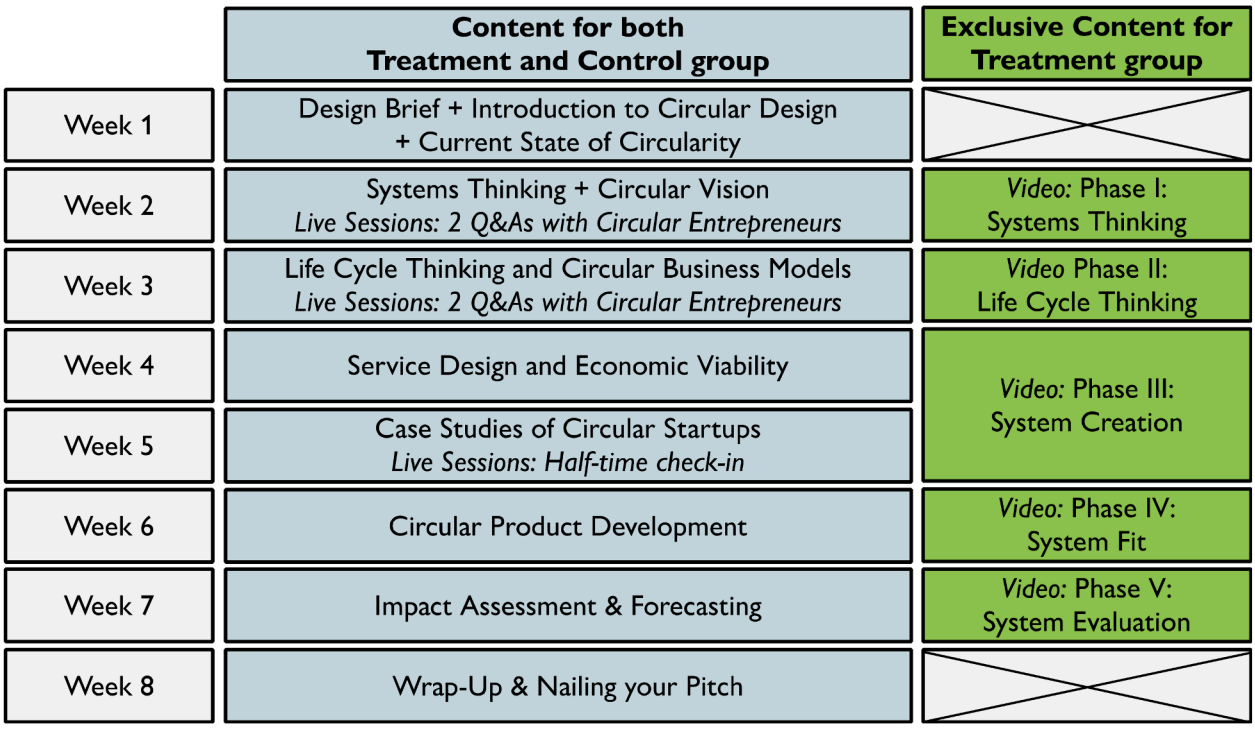


Fig. 3. Curriculum of the 8-week design challenge.

Table 3
Randomization checks.

	Treatment	Control	Difference	t	p
Age	31,3333	28,6667	2,6667	1,4268	0,2377
Gender	0,7593	0,6852	0,0741	0,8535	0,3322
Job Status	2,7037	2,7037	0	0	0,9197
Background = Business	0,4259	0,4630	−0,0370	−0,3837	0,8649
Background = Design	0,4630	0,4444	0,0185	0,1914	0,9859
Background = Engineering	0,1667	0,1852	−0,0185	−0,2502	0,7355
Background = Sustainability	0,4815	0,4815	0	0	0,8545
Background = Other	0,2222	0,2407	−0,0185	−0,2259	0,7414
Education	2,3519	2,5370	−0,1852	−0,9622	0,2200
Work Experience	1,6111	1,2963	0,3148	1,3790	0,2551
Entrepreneurial Experience	0,4815	0,3704	0,1111	1,1626	0,3209
Circular Design Experience	0,3148	0,2407	0,0741	0,7869	0,5011
Commitment	0,8148	0,75	0,0648	0,8276	0,3533

Leveraging empirical data, we constructed a comprehensive process blueprint using the second-order themes and third-order aggregate dimensions. The identified third-order aggregate dimensions describe the major phases of the CSD process (Fig. 6). The journey begins with *System Research* to understand the context in which entrepreneurs operate. This is followed by *Life Cycle Thinking* where they develop initial business models to improve an existing linear system. In *System Creation*, entrepreneurs develop complementary services and partnerships to enable their circular business model, before moving to *System Fit* where they align the product design with their chosen setup (e.g. optimize for durability or recyclability). The process concludes with *System Evaluation*, assessing the environmental impact of the CSD and inspiring subsequent iterations through potential shortcomings. This iterative approach, with its direct progressions and feedback loops, enables continuous refinement of circular systems.

System Research represents the first phase in the CSD process where entrepreneurial actors engage in systems thinking and mapping (Iacovidou et al., 2021), analyze the competitive landscape (D'Aveni, 2007), explore technological enablers (von Briel et al., 2018), understand and anticipate legislation (Davidsson et al., 2020), conduct consumer ethnography (Mariampolski, 2006), and model waste streams (Hines & Rich, 1997), supply chains (Burke et al., 2021), and the existing recycling infrastructure (Ribes & Finholt, 2009). The outcomes of this phase often reveal opportunities for circular value creation by identifying issues such as harmful waste streams, premature obsolescence, or inefficient supply chains. We also learned from interviews that entrepreneurs and designers would often formulate a vision for changing the status quo and assemble multidisciplinary teams with the necessary expertise to address the identified challenges.

Building upon these insights, the subsequent phase is ***Life Cycle Thinking***. This phase involves selecting an appropriate CBM archetype to improve the underlying product, component, or resource (Pieroni et al., 2020). These archetypes range from high-value retention to low-value retention (Achterberg et al., 2016; den Hollander et al., 2017), and are categorized into three overarching circular strategies relating to 'narrowing,' 'slowing,' and 'closing' resource loops (Bocken et al., 2016; Lüdeke-Freund et al., 2019). In the first life cycle, entrepreneurs typically select high-value retention archetypes, such as on-demand services or sharing business models. Beyond established archetypes, this phase presents an opportunity to innovate beyond conventional solutions,

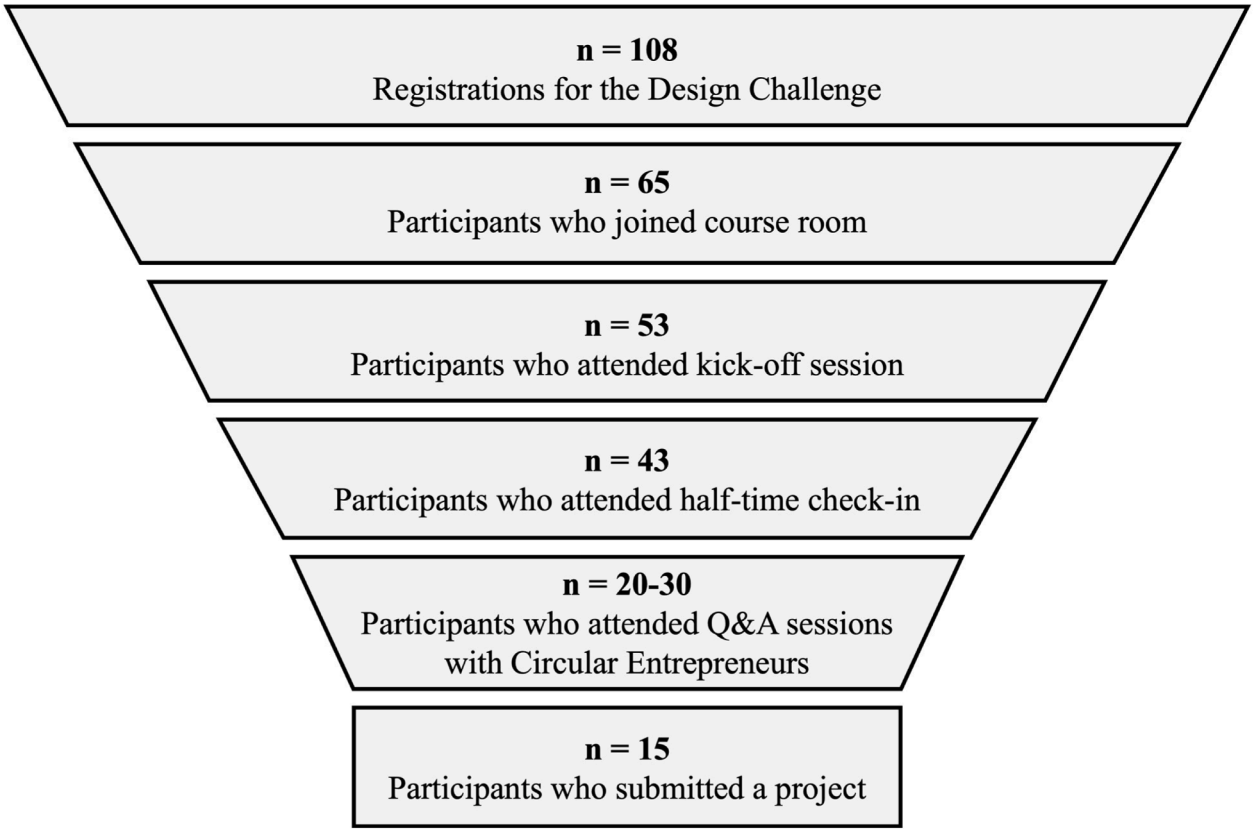


Fig. 4. Retention funnel during the design challenge.

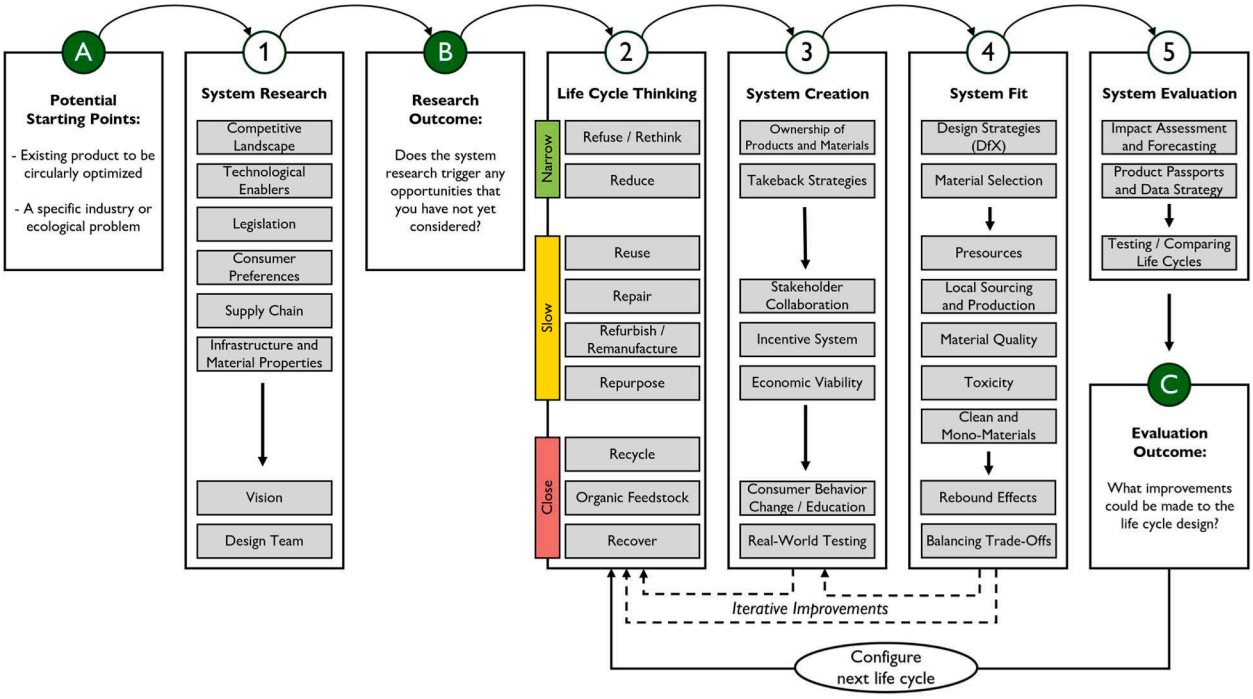


Fig. 5. Process blueprint for circular systems design.

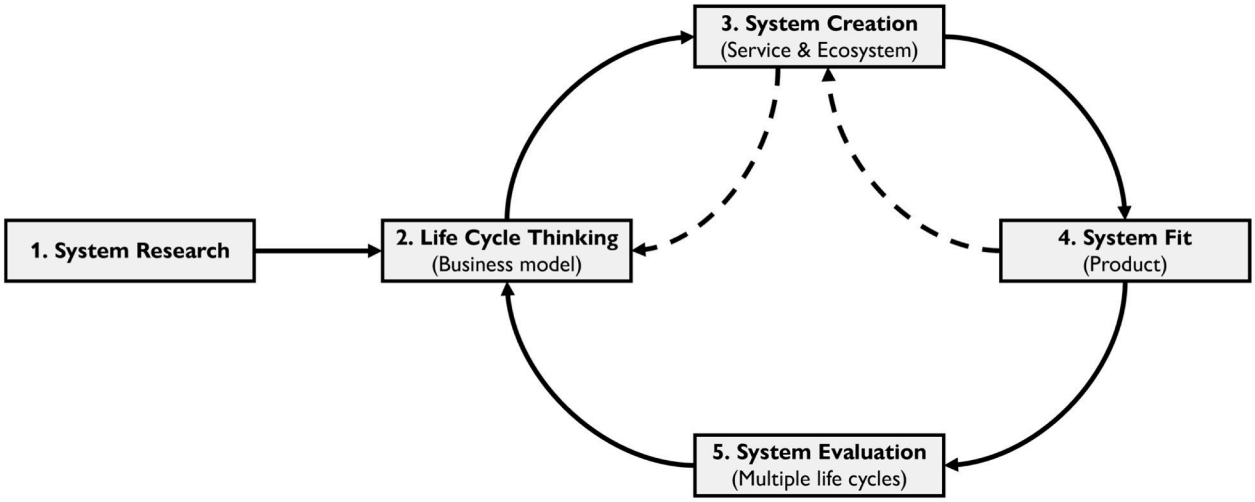


Fig. 6. Simplified CSD process.

potentially replacing existing products or services with fundamentally different approaches. The CSD process prompts entrepreneurs to anticipate potential end-of-life scenarios and chose an appropriate next archetype. For instance, a returned product might be repaired and refurbished for next-life sales. As products progress through multiple life cycles, entrepreneurs typically transition to archetypes with lower value retention, such as recycling and recovery (Stumpf et al., 2021). These often represent the final life cycle, where products deviate furthest from their original form and experience maximum compromise of product integrity. For example, materials may be repurposed for entirely different applications. As a last resort, obsolescent products may be incinerated to recover energy in the form of heat or electricity.

After imagining multiple life cycles, the CSD process advances to ***System Creation***. This phase focuses on service and ecosystem design, where entrepreneurs design customer interactions and enable the functioning of their CBM, which includes ownership models and take-back strategies. The central challenge of this phase is determining how to recover products when they become obsolete, either through physical deterioration or emotional detachment. A critical consideration is establishing appropriate compensation mechanisms to incentivize product returns. This phase requires careful alignment of stakeholder incentives to balance economic and ecological benefits, as system viability depends on customer behavior and willingness to pay. Startups typically employ a spectrum of increasingly powerful incentives, ranging from subtle nudging to vouchers to direct monetary compensation, depending on the value of the product. Subsequently, entrepreneurs design the ecosystem by establishing the necessary stakeholder collaborations to realize their selected CBM archetype. This often involves partnerships with logistics providers for returns or local collaborations to enable maintenance and repair archetypes. The phase concludes with comprehensive system testing involving all relevant stakeholders, including end consumers (Brown et al., 2021). This testing phase enables entrepreneurs to validate hypotheses and refine their business model, take-back strategies, and incentive systems to enhance circular system viability. As one entrepreneur in our sample noted, customer testing revealed insights that would have been impossible to anticipate during the life cycle thinking stage, highlighting the essential role of experimentation and user feedback in ensuring economic viability and minimizing rebound effects. The identified needs of collaborators and customers also inform concrete product design requirements. For instance, if product returns prove unfeasible, entrepreneurs must either modify their business model or optimize product design for recyclability. This consideration is especially relevant for low-value goods like packaging that are often discarded, in contrast to high-value products like electronics and smartphones, which consumers typically retain longer.

During the ***System Fit*** phase, the focus shifts to aligning the product with the designed circular system. This involves optimizing the product design and material selection (Mesa et al., 2020), including decisions about material quality and sourcing, local production capabilities, modularity, biodegradability, and recyclability. A key consideration is evaluating whether investments in higher-quality materials justify their premium costs within the circular business model. Entrepreneurs must also carefully balance trade-offs between product performance and sustainability (Luttropp & Lagerstedt, 2006). Maximizing sustainability at the expense of functionality can trigger rebound effects if consumers reject products due to inferior performance compared to linear alternatives. Many cite paper straws as a popular example for this challenge, as material degradation during use can lead to compromised user experience through altered taste and diminished functionality. This phase also addresses CER by ensuring product price and quality are competitive with linear solutions while implementing additional reduction mechanisms, such as educating customers through instructions (Castro et al., 2022). Many circular products integrate educational content into their packaging and encourage product registration through QR-codes to facilitate communication, returns, and ongoing customer engagement.

The final phase, ***System Evaluation,*** involves life cycle assessments (LCA) to measure the environmental impact of the circular system (Scheepens et al., 2016). This helps entrepreneurs to compare different design concepts and their outcomes. Entrepreneurs are also encouraged to formulate a data strategy for collecting and analyzing data for future improvements and to select suitable metrics, such as circularity, durability, and utilization (Boyer et al., 2021). A critical aspect is the iterative nature of this phase, including continuous data collection through sensors and product passports and investing in infrastructure and stakeholder capabilities to enhance data gathering and knowledge exchange. The System Evaluation phase typically initiates another cycle of

the CSD process as it reveals opportunities for improvement and other inefficiencies.

4.2. Rebound effect reduction

As previously described, CER manifests in two distinct ways. First, when increased levels of production and consumption negate initial environmental benefits; and second, when circular alternatives fail to displace linear products due to price or quality misalignment. Our analysis of whether CSD had the claimed potential to reduce CER revealed interesting insights.

Regarding consumption-based CER, participants acknowledged inherent limitations. As one designer noted, "the difficult part is simply the limited influence of a single company. It's perhaps more a matter of education and activism to control such things." Another entrepreneur emphasized: "even when building a circular business model, rebound effects still occur, it's not a cure-all. […] When Patagonia advertises not to buy new products, it's more of a stance. But ultimately, that's also marketing and doesn't prevent these effects." While one fashion entrepreneur in our sample incentivizes lower consumption by offering increasing discounts on one-to-one product exchanges based on the wear duration, the majority of participants view consumer education and industry advocacy as the primary lever for addressing this type of CER.

Participants expressed greater optimism about CSD's potential to address price and quality-related CER. While achieving desired quality posed some challenges, most participants pointed to cost as the primary barrier to reduce CER, as one participant explained: "Sustainability always means higher standards, and higher standards always mean higher costs. [.…In our current system, sustainability is inherently a competitive disadvantage. […] Sustainability is inherently more expensive, forcing us to think long-term." Rather than waiting for stricter environmental legislation to level the playing field, several participants described strategic CSD approaches that embrace a long-term perspective. One successful strategy involves gradual market penetration: "a bit more gradually might be the way to do it [.…having two product lines – a first one specifically focused on people that will invest in sustainability regardless and then feed that back into the primary production processes [to get the price right for the mainstream market]." This suggests that transitioning from a price-insensitive niche market to the mainstream market can be viable when entrepreneurs strategically plan the shift to preemptively address rebound concerns and leverage early adoption insights to optimize life cycle cost.

More significantly, entrepreneurs highlighted how CSD can systematically address price-quality barriers through innovative combinations of circular business models and product design. The potential of CSD lies in harmonizing these components. As one designer explained: "Bio-based alternatives are easily five times more expensive than virgin plastic. But if you have a take-back program and a fully circular system, investing in higher quality materials pays off as the value stays within the firm." This demonstrates how circular systems can transform apparent cost disadvantages into strategic advantages through higher value retention, as companies can monetize materials across multiple life cycles. However, economic parity then relies on long-term recuperation of initial investments. Consequently, robust take-back strategies enabled through CSD become crucial for offsetting the higher upfront costs of sustainable materials.

In addition, successful implementation often requires pragmatic compromises. One entrepreneur in sustainable packaging noted that "relying on customers to do things that are wildly inconvenient or more expensive is not reasonable." Such constraints often force entrepreneurs to prioritize economic viability at the expense of environmental performance: "[…] my preference would have been to produce in the UK. We spoke to over 200 manufacturers […] The cost of producing in UK is roughly 15 times the cost of producing it in China. With the tight margins in the packaging industry, we just couldn't have it produced in the UK." Beyond manufacturing costs, similar trade-offs emerge in material quality, product performance, and aesthetics, all of which can affect market adoption. As one designer explained: "sometimes users are just not accepting old products, so we need to make them look new." We also learnt about hygiene concerns from a designer working on baby products. Consumers' hesitation inspired a phased approach by first prioritizing recyclability despite lower value retention and then optimizing for durability in later iterations as consumers become more comfortable with reuse systems and develop trust in hygiene protocols.

CSD assists in balancing multiple trade-offs to reduce CER. These include balancing product performance with environmental impact, and weighing additional logistics and take-back costs against the value generated through repair and remanufacturing. The systemic approach also addresses financial trade-offs by evaluating upfront material investments against the profitability across multiple life cycles or assessing whether ownership retention is financially feasible. By systematically balancing economic, ecologic, and behavioral aspects, CSD helps reduce rebound effects by ensuring circular alternatives can effectively compete with and displace linear products in both quality and price dimensions.

4.3. First round of demonstration & evaluation

We clustered the feedback received during the 11 artifact workshops along the CSD phases. Throughout the artifact workshops, we received extensive and detailed feedback. An extended summary can be found in Appendix C. Each piece of feedback was thoroughly discussed between the authors for its relevance. The adaptation of the process blueprint led to the final artifact, which we have coined the Circular Systems Sandbox (Appendix D).

4.3.1. Feedback system research

The System Research phase received positive feedback throughout for its role in enabling critical thinking and information gathering for the rest of the CSD process:

> "*It makes sense that you start by research"* (Interviewee 3).

Yet, workshop participants suggested further improvements to the artifact. Specifically, they pointed out that available materials could also be a potential starting point for the process. Therefore, we decided to integrate materials as a third starting point of our artifact, complementing problematic linear products and specific industries:

> "I*t's very interesting to start from a material perspective as well […], because we're always trying to replace other products […]. But some materials can't be replaced. So, we are looking into new materials that have a different approach that have different specifics*" (Interviewee 3).

4.3.2. Feedback life cycle thinking

For the Life Cycle Thinking phase, the feedback was again positive in terms of structure and content. The tool received praise for the "traffic light" logic that is connected to high, medium and low value retention strategies, which we decided to keep as a central element of our artifact:

> "*I really like the idea of having this kind of green, yellow, red. Yeah, I think it's very useful*" (Interviewee 4).

For this phase, we again sought potential improvements. Workshop participants suggested various aspects to further develop the artifact. One notable aspect was the extensive time horizon for the Life Cycle Thinking phase. To address this, we decided to integrate this by adding a description of parameters to the artifact's starting section:

> "*Well, yeah, because[…] if you're doing multiple life cycles […]. It can take a lot of time, right? If you're doing the research for each of those different life cycles, with different strategies even*" (Interviewee 10).

4.3.3. Feedback system creation

The System Creation phase received positive feedback for the prominent integration of take-back strategies as the phase's starting point. Workshop participants emphasized the importance of these strategies for a product's overall circularity:

> "*To me the most crucial point is to try to understand if your product can be circular. That is the first thing that […] you need to look at the take-back system*" (Interviewee 4).

The feedback also identified points for improvement, primarily concerning its overall complexity. Based on this feedback, we decided to reduce the complexity by adding a canvas-inspired table to help maintain an overview of stakeholder collaborations for the CBM:

> "*What I find complicated is phase three to be honest because you have so many things there. So, that can be overwhelming. […] I would simplify this column […]. Maybe you can just find a simplified version of the business model canvas or even create your own business model canvas with just 3 or 4 boxes*" (Interviewee 7).

4.3.4. Feedback system fit

The System Fit phase received positive feedback, particularly regarding how its name conceptually complements the other phases:

> "I *really like the name "System Fit". I feel like that's also what I mean in terms of evaluating if the product actually fits the system that you have designed. […] Because then in that sense you can go through iterations in design also to make it fit*" (Interviewee 2).

Points of improvement were outlined concerning the material selection process. Specifically, the structuring of material selection should be adapted to focus on material properties. The information should be provided in a way that allows users to select the properties they require. Based on this feedback, we added a multiple-choice logic and the "Knowledge Base" as a repository of additional explanations and information around material properties and design strategies. This provides increased guidance and inspiration to the user:

> "*Maybe doing a checkbox element. […] Maybe you can just ask a question if the materials that you intend to use are toxic or not. […] Because this is very broad and generic, but I would make it a little bit more specific*" (Interviewee 4).

4.3.5. Feedback system evaluation

The feedback for the System Evaluation phase was positive. The main response was that the processual structure and the timing mirror a good design process:

> "*Yeah. I mean, also the good thing about testing it with people is that we can really ask later […]. But I agree that it's something that should come later in general. So, I think it is fine*" (Interviewee 7).

Suggestions for further improvement concerned the method of evaluation. Instead of requiring a comprehensive LCA, workshop participants suggested simplifying the evaluation task to focus on CO2 emissions. Following this input, we decided to link to complementary LCA tools while incorporating a simplified impact evaluation into the artifact to reduce complexity:

> "*Why don't you make this simpler? Because I agree with you. LCA is really complicated. […] Even in my case, they explained to me 2 or 3 times how LCA works. […] Why don't you decide to focus instead of LCA, for example, just on the CO2 emissions?*" (Interviewee 4).

4.4. Second round of demonstration & evaluation

The second round of demonstration and evaluation took the form of a randomized controlled trial which we conducted between February and April 2024 in collaboration with an international design academy. Out of 15 total project submissions, five projects worked extensively with the *Circular Systems Sandbox*. The empirical results supported our hypotheses: participants with access to the artifact demonstrated superior performance compared to those using alternative tools, showing particular strength in design completeness, business model viability, and rebound effect reduction (Table 4).

The systemic integration of CER reduction into the CSS enabled significantly better performance in the treatment group for both quality rebound ($p < 0.05$) and price rebound ($p <$ v0.1). Participants using the CSS expressed reduced rebound effects through strategic design choices and business models such as focusing on dematerialization, durable materials, and take-back systems, while simultaneously selecting circular business model archetypes with higher value retention like Access and Sharing Models. These proposed solutions both minimize lifecycle costs and lower entry barriers compared to traditional ownership. For example, one team from Spain demonstrated and tested the implementation of a communal water station that eliminated the need for individual PET bottle purchases from retailers, thereby reducing both environmental impact and costs.

Treatment group participants also developed more systemic and complete designs ($p < 0.1$), integrating design levels more thoroughly compared to control group participants. This shows that an integrated process tool may facilitate CSD more than using several disjointed tools. Business model viability was another strength of CSS submissions. This can be attributed to the tool's emphasis on early and frequent hypothesis testing and user feedback. While three of five treatment group submissions conducted stakeholder tests, only one of ten control group projects engaged with stakeholders and developed a working prototype.

We checked whether participants who submitted projects in the treatment group were different from those in the control group, such as being more skilled or experienced. We found no statistically significant differences between submissions in the treatment and control groups. Additionally, we examined differences between those who submitted a project in either the treatment or control group and those who dropped out of the challenge or did not submit a project (Table 5). First, project

Table 4
Experiment results.

	Circular Systems Sandbox			
	Treatment N = 5	Control N = 10		
Variables	Average rank	Average rank	U	p
Design Completeness*	4,8	9,6	9	0,0572
Design Innovativeness	6	9	15	0,3527
Methodology	5,6	9,2	13	0,1586
Impact Potential	5,4	9,3	12	0,1388
Resource Efficiency	5,8	9,1	14	0,2429
Scalability	5,8	9,1	14	0,1564
Innovation Viability**	4,6	9,7	8	0,0484
Innovation Feasibility	5,2	9,4	11	0,1503
Rebound Quality**	4,4	9,8	7	0,0221
Rebound Price*	5,4	9,3	12	0,0711
Total*	4,8	9,6	9	0,0576

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$ | 1 = Highest Rank; 15 = Lowest Rank.

Table 5
Participant characteristics by project submission status.

	Submission	No Submission	Difference	t	p
Age	29,4705	30,0989	−0,6283	−0,2657	0,8085
Gender	0,8824	0,6923	0,1900	2,0196	0,1103
Job Status**	2	2,8352	−0,8352	−2,3953	**0,01712
Background = Business	0,4706	0,4396	0,0310	0,2293	0,8153
Background = Design	0,3529	0,4725	−0,1196	−0,9160	0,6798
Background = Engineering	0,2941	0,1538	0,1403	1,1680	0,1663
Background = Sustainability**	0,7059	0,4396	0,2663	2,1246	**0,0441
Background = Other	0,3529	0,2088	0,1441	1,1357	0,1993
Education	2,3529	2,4615	−0,1086	−0,4113	0,6854
Work Experience	1,5882	1,4286	0,1597	0,5550	0,6130
Entrepreneurial Experience	0,4706	0,4176	0,0530	0,3921	0,6883
Circular Design Experience	0,2353	0,2857	−0,0504	−0,4261	0,6987
Commitment	0,8824	0,7637	0,1186	1,2941	0,2708

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 6
Results of the exit survey.

	Mean Treatment ($n = 8$)	Mean Control ($n = 14$)	t-Values
Enjoyment of the challenge	6,50	6,07	0.306
Satisfaction with course room	6,63	6,29	0.308
Learning Progress	6,25	5,64	0.126
Confidence in design ability	6,00	5,50	0.267
Quality of own idea/solution	4,88	4,21	0.3
Level of challenge	4,75	5,29	0.195
Ease of Use	4,50	5,00	0.592
Usefulness	5,63	5,33	0.616
Recommendation	6,25	5,83	0.494
Well-being and project stability	4,88	4,83	0.944

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

completion rates were higher among unemployed individuals and students, likely due to greater time flexibility and stronger career development motivations. Full-time employed participants showed lower completion rates, presumably due to competing work commitments. Second, participants with sustainability backgrounds demonstrated higher submission rates compared to those with business or design backgrounds, suggesting stronger intrinsic motivation to engage with CE projects.

In addition to the jury evaluation of the project submissions, we created an exit survey which aimed to gather feedback from participants. The exit survey was completed separately by the treatment group and the control group, with questions tailored to each group's toolbox. The treatment group was specifically asked about their experience using the Circular Systems Sandbox, while the control group was asked about their experience using comparable tools. In total, we received 22 responses, 8 for the treatment and 14 for the control group. We conducted *t*-tests to test for statistically significant differences between the two groups (Table 6). Given the small sample size, none of the questions showed statistically significant differences. However, when comparing the mean values, we observed a clear tendency toward the treatment group, with nine out of ten mean values being rated higher than those of the control group. The degree of challenge encountered during the project was rated in reverse order, with the treatment group encountering a lower average level of challenge. The only question where the control group scored higher was regarding the tools' ease of use. This makes sense given the complexity of the CSD process, yet it appears that despite the tool being perceived as more complex, it might simultaneously reduce the perceived difficulty of the challenge. We conclude that participants using the Circular Systems Sandbox, on average, enjoyed the challenge more, were more satisfied with the course experience, learned more during the challenge, feel more confident in their ability to apply circular design concepts in the future, and were more confident in the quality of their CSD. The tool comparison revealed that participants found the Circular Systems Sandbox more useful than other tools and were more likely to recommend it. However, we note that there might be room for making the tool easier to use. Although not statistically significant, it is noticeable that fewer people completed the project using the CSS, which can be attributed to the greater time and effort required.

5. Discussion

5.1. Circular systems design and the entrepreneurial journey

The present study advances our understanding of CSD by empirically demonstrating the intricate interconnections between circular design levels. From an entrepreneurial perspective, CSD follows an outside-in process: entrepreneurs first identify value loss points in the linear

system that present opportunities for ecological and economic improvement, then progressively work inward from these system-level opportunities toward more granular and detailed design decisions, such as product specifications. While Baldassarre et al. (2020) have positioned CBM design as embedded in collaborative ecosystem design, we find that entrepreneurs typically begin with CBM design as entrepreneurs naturally pursue their own commercial interests before optimizing ecosystem-wide benefits (Dean & McMullen, 2007; Pacheco et al., 2010). Accordingly, the entrepreneur first imagines a more efficient life cycle design with a corresponding CBM and then proceeds to engage key stakeholders to develop the collaborative ecosystem and enable their envisioned CBM. Therefore, entrepreneurs often consider themselves "orchestrators" (Aarikka-Stenroos et al., 2021). Speaking figuratively, orchestrators conceive a vision for the entire life cycle of a product for which they seek collaborators to realize their idea of a Circular Economy.

Therefore, the CSD process moves from *System Research* to *Life Cycle Thinking*, iteratively improving economic and ecologic benefits with collaborators during *System Creation*. Subsequently, the previous configuration is translated into material properties, modules and other product design features during *System Fit*. A thorough analysis of the CSD constitutes the last phase in the form of a *System Evaluation*. According to our results, starting with an LCA is not advisable, since material decisions gain meaning only within established CBMs (i.e. the current life cycle). Instead, we observed that successful CSD finishes with an in-depth system evaluation, ideally making use of LCA to inspire and compare new scenarios and find iterative improvements.

Our research integrated previously isolated literature streams on CPD (e.g., den Hollander et al., 2017), PSS design (e.g., Moro et al., 2022), CBM design (e.g., Geissdoerfer et al., 2020), and collaborative ecosystem design (e.g., Konietzko et al., 2020), which in combination constitute CSD (Remke & Müller, 2024). We have not only theorized their interdependencies but also practically validated the CSD framework with circular design experts and successful circular entrepreneurs. Giving meaning to the inner functioning of CSD aligns with calls for more systemic approaches to the CE (Iacovidou et al., 2021; Kirchherr, 2023), while advancing literature across circular design and business model innovation.

Finally, entrepreneurs have been described as trailblazers in the circular transformation (Bauwens et al., 2019), however, we want to specify that entrepreneurs' success largely depends on collaboration with incumbent actors rather than disruption and advocacy. This partnership approach is crucial as circular system viability is contingent on long-term thinking and stakeholder buy-in to become profitable over extended periods of time. This is necessary to avoid the creation of niche products that fail to scale and achieve meaningful impact thereby leading to CER. However, we also note that the complexity of CSD makes it particularly suited to entrepreneurial ventures, which enjoy greater design freedom and experimental capacity than incumbent firms constrained by their existing value creation systems.

5.2. Mechanisms for circular rebound reduction

Our second contribution lies in explaining how CSD proactively reduces CER (Figge & Thorpe, 2019; Metic & Pigosso, 2022; Zink & Geyer, 2017). We posit that the primary mechanism for CER reduction is the systematic evaluation of trade-offs across design levels to optimize the price and quality of circular offerings. We also found mechanisms for addressing overconsumption, for example, through educating consumers or by optimizing incentives and pricing for longer use, yet the main strength of CSD lies in tailoring a circular product or service for the mainstream market.

CSD helps entrepreneurs to achieve competitiveness with linear alternatives while also achieving environmental benefits. Our tool guides entrepreneurs in considering how their design choices affect both production and consumption patterns and the resulting environmental impacts across multiple life cycles. To understand their design choices, real-world tests prove essential to ensure that products and services are utilized as intended (Brown et al., 2021). Therefore, we posit that small-scale experimentation serves as an effective method for identifying CER, as entrepreneurs pay attention to any deviations from expected stakeholder behavior that may indicate CER. This ensures that products and services are neither overused, misused or unfit to meet user requirements. The CSD process addresses identified issues by prompting the reevaluation of certain design decisions, including modifications to the CBM or CPD, adding collaborations with stakeholders, or refining the incentive structure. Overall, entrepreneurs are enabled to identify and understand trade-offs resulting from circular design strategies and material choices, such as product performance vs. environmental impact and additional logistics vs. added value from repair or remanufacturing. This forward-looking approach helps entrepreneurs reduce CER preemptively before entering the market. As CSD considers multiple life cycles, higher expenses for more durable materials, added services, or logistics can often be spread over several life cycles, enhancing cost-effectiveness and long-term profitability. Consequently, takeback strategies and ownership models are some of the most critical elements in CSD to ensure proper functioning and avoid price-related CER.

While rebound effects are inherently challenging to identify and measure due to their unpredictable nature, our study demonstrates how CSD can anticipate and proactively reduce CER. Although the ex-ante nature of CSD precludes precise quantitative assessment, its theoretical foundation provides a framework for making sense of its capabilities for reducing CER (Zink & Geyer, 2017). However, CSD is not a complete solution, as certain rebound effects like overconsumption, remain difficult to anticipate prior to the final market introduction. Therefore, entrepreneurs should combine CSD with complementary strategies identified through our interviews and supported by existing literature, such as activism for reducing consumption or lobbying for environmental policy to reduce CER (Castro et al., 2022; Zerbino, 2022).

5.3. Practical artifact for circular systems design and circular rebound reduction

This study also makes a significant practical contribution by developing and empirically validating the first comprehensive tool for CSD, addressing the pressing need for systemic solutions in the sustainability transition (Baldassarre et al., 2020; den Hollander et al., 2017; Kirchherr, 2023). The *Circular Systems Sandbox* represents a significant advancement in helping entrepreneurs design circular systems that can effectively compete with linear alternatives in both quality and price (Zink & Geyer, 2017). This innovative tool builds upon and extends established entrepreneurial frameworks like the Business Model Canvas (Osterwalder et al., 2010) or the Lean Startup Framework (Blank & Eckhardt, 2023). While previously entrepreneurs had to navigate a fragmented landscape of design tools for CPD (e.g., Franconi et al., 2022) and CBM (e.g., Das et al., 2023), our tool integrates these crucial elements alongside PSS and collaborative ecosystem design into a cohesive and holistic framework. Overall, the main strengths of our tool are a structured and methodological process for entrepreneurs to develop systems, validate their functioning, and reducing rebound effects through optimizing design trade-offs. The CSS incorporates insights and lessons from experienced circular entrepreneurs and design experts, providing future generations of entrepreneurs and researchers with an extensive framework for establishing circular systems and accelerating the sustainability transition.

6. Limitations and future research

6.1. Tool limitations and boundary conditions

The CSS, while providing a structured approach to CSD, has several important limitations. First, although it breaks down the design process

into manageable steps, successful execution requires substantial domain knowledge, with failure remaining a natural part of the innovation process. Our tool focuses on facilitating systemic design rather than guaranteeing business success, serving primarily as a structured framework for considering critical aspects in circular entrepreneurship. Second, the tool was perceived as rather comprehensive and complex. Its multi-faceted approach, while necessary for addressing system-level challenges, demands considerable time investment from users. Implementation can span months depending on the complexity of the system, making it more suitable for incubation programs than CBM ideation sessions in the board room. Our empirical observations suggest that this complexity may affect completion rates, indicating a need for simpler tools for rapid experimentation. Third, while effective at addressing price and quality-related rebound effects, the tool only partially tackles consumption and production-level rebounds, which often require broader industry advocacy and consumer education. Fourth, the tool shows particular strength when applied to startups centered around physical entities like products, components, or materials. Its utility diminishes for purely digital solutions such as software for supply chain monitoring, though these solutions also contribute to circular economy advancement. The tool also lacks detailed financial calculation capabilities, particularly for considerations regarding multiple life cycles, presenting an opportunity for complementary solutions that could significantly enhance entrepreneurial success.

6.2. Study limitations and research opportunities

Our study has several methodological limitations that also hold promising directions for future research. First, the experimental evaluation produced a limited sample of 15 project submissions. While providing promising initial results, the tool would benefit from additional design challenges to strengthen observed effects and clarify the tool's effectiveness. Second, our experimental setting sampled individuals interested in circular design from the general public. This limits our ability to draw broader conclusions about the tool's impact on startup success rates; redoing this exercise within an incubator setting or a similar environment could provide more definitive insights into its practical effectiveness. Third, we utilized custom measurement constructs instead of established scales to evaluate the projects. Although we developed detailed judging rubrics to ensure consistency, these may not capture all relevant dimensions of CSD. While we implemented blind reviews and inter-rater reliability checks to maintain objectivity and reliability, the inherent subjectivity in the chosen dimensions cannot be entirely eliminated.

Additionally, the CSD process could be adapted and tested in different contexts requiring systemic approaches, such as mobility solutions or energy systems. Future versions of the artifact could also incorporate emerging concepts like sufficiency, regeneration, and degrowth (Konietzko et al., 2023). Replication studies could further validate our findings while enhancing our artifact by creating streamlined versions for ideation sessions or comprehensive implementations within incubation programs. Further, advancing the measurement and understanding of CER still represents a critical research opportunity and requires more work. Developing robust measurement methods would significantly improve our ability to assess and mitigate these effects. Additionally, future research could explore patterns across life cycles, as we typically observe a cascade from high to low value retention strategies. Finally, given the long-term horizon needed to achieve economic viability in CSD, longitudinal studies could investigate how organizations manage this extended timeline and incorporate learnings into their CSD.

7. Conclusion

Our study advances both theory and practice of Circular System Design. Theoretically, we extend the CSD concept and develop an iterative design process (Remke & Müller, 2024), while empirically validating its potential to reduce CER (Zink & Geyer, 2017), thereby addressing a central concern in the ongoing discourse about the CE (Corvellec et al., 2022). This study further contributes profoundly in a practical manner by applying a mixed-methods DSR approach to develop a valuable tool for entrepreneurs. Through this paper, we aim to inspire future research in the field of CSD and advocate for design-oriented research approaches to move closer to executing on the sustainability transition and the potential of the CE.

Fundings

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Use of AI tools

During the preparation of this work the author(s) used ChatGPT in order to copyedit selected paragraphs in the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Henry Willem Müller: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Konstantin Remke:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We express our gratitude to our colleagues at the international design academy for their pivotal role in organizing and facilitating the design challenge.

Appendix A. Review of tool landscape

(Fig. A1).

		Type								Adapted from Baldassarre et al. (2020)						Other Aspects	
Tool Name	Authors	Book & Report	Principles, Guidelines, Strategies	Framework	Toolkit (Set of Templates)	Workshop	Canvas	Software-Tool & Database	Game & Cards	Resources, Material, Component	Product	PSS	Business Model	Ecosystem	System	Process Depiction	Industry
The Circular Design Guide	IDEO & Ellen MacArthur Foundation				x						x						Agnostic
10 Circular Design Guidelines	Diez Office		x								x						Agnostic
Circular Design Toolkit	Interreg Baltic Sea Region & Fraunhofer IZM				x								x			x	Agnostic
Circular Business Model Design Guide	Ellen MacArthur Foundation & PAConsulting	x											x				Agnostic
Design for X Tool	Circular Design (Franconi, Terzioglu, Fregoni, Carvalho, Ghoreishi)							x			x						Agnostic
Circular Redesign Workshop Tookit	Unschool				x						x					x	Agnostic
Katch-e Design Tool	Katch-e							x					x			x	Agnostic
Kickstarter Environmental Resource Guide	Kickstarter & Environmental Defense Fund		x							x							Agnostic
Zero Waste Hierarchy	Zero Waste Europe			x						x							Agnostic
Systemic Four	Future Urban Living				x							x					Agnostic
Circular Design Guidelines	Lissalde Studio		x								x						Agnostic
"+Circular Design Tool"	Witteven Bos				x						x					x	Agnostic
Shift Toolkit	SITRA (White & Habib)				x						x						Agnostic
Use2Use Design Toolkit	Use2Use				x								x			x	Agnostic
Circularity Deck	TU Delft (Konietzko, Bocken, Hultink)		x								x						Agnostic
The Ten Cards	Centre for Circular Design								x		x						Agnostic
Designing your Circular Transition Toolkit	DDC				x						x						Agnostic
Circular Strategies Scanner; Guidelines for Circular Product Development; Circularity Assessment Tool	CIRCit Nord		x					x			x					x	Agnostic
Circular Design Guidebook	Covestro & REnato Lab	x	x								x						Agnostic
The Circular Design Toolkit	Circulab Academy				x									x		x	Agnostic
Circular Economy Toolkit	University of Cambridge, Institute for Manufacturing (Evans, Bocken)				x						x					x	Agnostic
Circular Design Framework; The Nordic Circular Playbook 2.0; Quantitative analysis of circular economy strategies; Three Dimensions of Circularity	Nordic Circular Hotspot			x							x						Agnostic
AskNature Database	Biomimicry Institute							x			x						Agnostic
Value Recapture Brainwriting	University of Limerick (Bakirlioglu & McMahon)				x						x						Agnostic
MATChE Methods	ready2Loop & Novo Nordisk		x								x						Agnostic
Circular Tool	Matrec & Bureau Veritas				x					x						x	Agnostic
Ressourcencheck	Ressourcenforum Austria							x		x							Agnostic
VDI-ZRE Tool	VDI Zentrum Ressourceneffizienz							x		x						x	Agnostic
Make it circular!	acatech, WWF Germany, Circular Economy Initiative								x				x				Agnostic
Kriterienmatrix	Bundespreis Ecodesign			x							x						Agnostic
PROBAS	Umweltbundesamt Germany							x			x						Agnostic
IDEMAT - LCA light als App	TU Delft (Meursing, Vogtländer)							x		x						x	Agnostic
Ecolizer	OVAM (Belgium)							x		x						x	Agnostic
Ecodesign Pilot	TU Wien							x			x					x	Agnostic
Handlungsempfehlungen für die Produktentwicklung	VDI Zentrum Ressourceneffizienz							x			x					x	Agnostic
Transition Design Guide	Wuppertal Institut für Klima, Umwelt, Energie & Folkwang Universität der Künste	x	x								x						Agnostic
Venturewell Tools	National Collegiate Inventors and Innovators Alliance, d/b/a VentureWell (USA)				x						x					x	Agnostic
Biomimicry Toolbox	Biomimicry Institute	x	x								x						Agnostic
Baukasten "Design für Ressourceneffizienz"	VDI-Zentrum Ressourceneffizienz				x					x							Agnostic
Circular Design Rules	Institute of Design Research Vienna (IDRV) & designaustria		x								x						Agnostic
Katch-e The 10 Essentials	Katch-e	x	x								x						Agnostic
Diter Rams - Ten Theses for Good Design	Dieter Rams & Vitsoe	x	x								x						Agnostic
Circular Experience Library	Circular-Experience.org							x			x						Agnostic

Fig. A1. Tool overview.

			Type								Adapted from Baldassarre et al. (2020)						Other Aspects	
Tool Name	Authors	Journal	Article	Principles, Guidelines, Strategies	Framework	Method	Workshop	Canvas	Software-Tool & Database	Game & Cards	Resources, Material, Component	Product	PSS	Business Model	Ecosystem	System	Process Depiction	Industry
CD-TOOLS for Product Integrity	Cautela, Dagiliene, Valusyte	*IEEE International Conference on Technology and Entrepreneurship*	x						x			x						Agnostic
Circular Collaboration Canvas	Brown, Baldassare, Konietzko, Bocken, Balkenende	*Journal of Cleaner Production*	x					x							x			Agnostic
Circular Design Framework	Moreno, De Los Rios, Rowe, Charnley	*Sustainability*	x		x							x						Agnostic
Resource Pressure Design Method	Desing, Braun, Hischier	*Resources, Conservation, and Recycling*	x			x					x							Agnostic
Circular Economy Product and Business Model Strategy Framework	Bocken, de Pauw, Bakker, van der Grinten	*Journal of Industrial and Production Engineering*	x		x									x				Agnostic
Circular Material Library	Virtanen, Manskinen, Eerola	*The Design Journal*	x						x		x							Agnostic
Multiple Loops Life Cycle Design Approach for the Circular Economy	Mestre & Cooper	*The Design Journal*	x		x							x						Agnostic
Circular Pathfinder	van Dam, Bakker, de Pauw, van der Grinten	*PLATE: Product Lifetimes And The Environment*	x		x							x						Agnostic
Roadmap for Circular Product Design	Wang, Burke, Zhang	*International Journal of Production Economics*	x		x							x						Agnostic
Key Competencies for Design in a Circular Economy	Sumter, de Koning, Bakker, Balkenende	*Sustainability*	x	x								x						Agnostic
The Circular Business Model Canvas	Lewandowski	*Sustainability*	x					x						x				Agnostic
The Circular Strategy Scanner & Design Guidelines	Shahbazi, Jönbrink	*Sustainability*	x	x	x							x						Agnostic
Metrics-based Product Evaluation Framework	Hapuwatte & Jawahir	*Industrial Ecology*	x		x							x						Agnostic
The Circular Sprint	Santa-Maria, Vermeulen, Baumgartner	*Journal of Cleaner Production*	x			x	x							x			x	Agnostic
Circular Business Framework	Lauten-Weiss, Ramesohl	*Sustainability*	x		x									x				Agnostic
Circular Business Model Tool	Geissdoerfer, Pieroni, Pigosso, Soufani	*Journal of Cleaner Production*	x		x			x						x				Agnostic
Design Thinking Framework for Circular Business Model Innovation	Guldmann, Bocken, Brezet	*Journal of Business Models*	x		x									x			x	Agnostic
Framework for Sustainable Circular Business Model Innovation	Antikainen & Valkokari	*Technology Innovatio Management Review*	x		x									x				Agnostic
Circular Business Model Mapping Tool	Nußholz	*Journal of Cleaner Production*	x					x						x				Agnostic
The Circular Rebound Tool	Das, Konietzko, Bocken, Dijk	*Resources, Conservation, and Recycling Advances*	x			x	x							x			x	Agnostic
Product Design Framework for a Circular Economy	van den Berg & Bakker	*PLATE: Product Lifetimes And The Environment*	x		x							x						Agnostic
In the Loop: The Critical Raw Materials Game	Whalen & Peck	*International Journal of Automation Technology*	x							x	x							Agnostic

Fig. A1. (*continued*).

Appendix B. Scoring sheet with judging rubrics

(Fig. B1).

Task	Outcome / Goals				Score
Design a circular system that entails a circular product or service embedded within a circular business model and a collaborative ecosystem	The resulting circular system should be comparable in quality, price, and target market with competing linear products/systems				Awarded Points
Criteria	**0-3 points**	**4-6 points**	**7-8 points**	**9-10 points**	**Score**
Design: Completeness	Evaluates how thoroughly the design addresses all relevant aspects. A complete design should cover all components including product/service, business model, and collaborative ecosystem.	Design is incomplete, with substantial gaps or essential elements missing. Lack of coherence and integration.	Partial completeness, addressing some elements but lacking a comprehensive approach. Not all aspects are adequately covered.	Mostly complete design, covering key aspects and demonstrating a good understanding of the circular economy. Some minor gaps may still be present.	Comprehensive and fully complete design. Thoroughly addresses all relevant elements of the circular economy, demonstrating a holistic approach.	0
Design: Innovativeness / Originality	Assesses the level of creativity and uniqueness in the design. An innovative and original design introduces new and imaginative elements.	Low innovativeness, lacking original ideas. The design fails to introduce novel or creative elements.	Moderate innovativeness, incorporating some creative elements but lacking depth and uniqueness.	High innovativeness, demonstrating creativity with original ideas that contribute to the advancement of circular economy practices.	Exceptional innovativeness, showcasing groundbreaking and original ideas that significantly contribute to the field.	0
Approach/ Methodology	Examines the rigor and clarity of the approach used in developing the circular system. A well-defined and scientifically grounded approach involves testing hypotheses, validating ideas and framing problems.	Weak or inadequately tested methodology. Assumptions lack rigorous testing, and evidence-based decision-making is limited.	Adequate methodology with some testing of assumptions. Evidence-based reasoning is present but may have some gaps or limitations.	Solid methodology with thorough assumption testing. The approach is evidence-based, demonstrating a good understanding of potential challenges and solutions.	Excellent and well-tested methodology. Assumptions are rigorously tested, and the project relies heavily on evidence-based decision-making, showcasing a robust and reliable approach.	0
Impact Potential	Focuses on the potential positive environmental impact of the designed circular system. A high-scoring project should demonstrate a deep commitment to sustainability, showcasing how the circular system contributes to environmental conservation.	Low potential impact against the baseline scenario of linear alternatives. Fails to address or minimally mitigates the environmental problem at hand.	Moderate potential impact with some improvement over linear alternatives. Addresses the environmental problem to a certain extent but lacks a regenerative approach.	High potential impact against the baseline scenario of linear alternatives. Demonstrates a significant improvement in addressing the environmental problem, showcasing elements of positive impact.	Exceptional potential impact. The project not only surpasses linear alternatives but also adopts regenerative approaches, contributing significantly to environmental restoration and sustainability.	0
Resource Efficiency/ Life Cycle	Examines the efficient utilization of various resources across the entire life cycle from material sourcing to disposal. It examines if the design optimizes resource use and outlines plans for slowing and closing loops.	Inefficient design with poor consideration of the product life cycle. Significant oversights in resource optimization and waste reduction.	Moderate efficiency with some life cycle considerations. Addresses some aspects but lacks a comprehensive approach.	Efficient design with a good understanding of the life cycle. Demonstrates effective resource management and waste reduction.	Highly efficient, demonstrating a comprehensive life cycle approach. Optimizes resources at every stage with minimal waste.	0
Scalability	Evaluates the scalability of the proposed circular system. Scalability is crucial for widespread adoption. A scalable design should outline clear considerations for growth and expansion.	Limited scalability or poorly addressed scalability. No indication of seamless rollout or potential adoption elsewhere. Lacks a blueprint for widespread implementation.	Moderate scalability with some considerations. Shows potential for growth but lacks a clear plan or blueprint for seamless adoption in different contexts.	Good scalability, demonstrating potential for growth with a clear blueprint for expansion. The design suggests it can be adopted elsewhere with some modifications.	Highly scalable, with a well-defined blueprint for expansion and widespread adoption. The system is designed for seamless rollout and adoption in various contexts.	0
Criteria	**Description / Notes**	**0-1 points**	**2-3 points**	**4 points**	**5 points**	**Score**
Innovation: Viability (Cultural)	Evaluates the cultural acceptance and relevance of the circular system. A high score indicates that the design aligns with cultural values, norms, and preferences, ensuring that it can be seamlessly integrated into the societal context.	Limited viability. Fails to align with user behavior or ensure economic sustainability.	Moderate viability. Addresses some aspects of user behavior but needs improvement in ensuring economic sustainability.	Strong viability. Demonstrates alignment with user behavior and shows indications of economic sustainability.	Exceptional cultural viability. Successfully aligns with and positively influences user behavior, ensuring strong economic sustainability.	0
Innovation: Feasability (Scientific)	Assesses the soundness and practicality of the proposed circular system from a scientific and technical perspective.	Limited scientific feasibility. Lacks technical realism.	Moderate scientific feasibility. Demonstrates some technical realism but lacks depth.	Strong scientific feasibility. Provides a technical realistic and feasible approach.	Exceptional scientific feasibility. Demonstrates a highly realistic and doable technical angle, ensuring practical implementation.	0
Rebound: Comparable in Quality	Evaluates how well the circular economy system maintains ol exceeds the quality standards set by linear alternatives. A higher score indicates that the proposed solution not only meets but potentially enhances the quality of products or services.	Poor rebound mitigation for quality. Significant quality issues compared to linear alternatives.	Moderate rebound mitigation for quality. Shows some effort but quality concerns remain.	Good rebound mitigation for quality. Demonstrates balanced or improved quality compared to linear alternatives.	Excellent rebound mitigation for quality. Maintains or enhances quality, minimizing potential negative impacts.	0
Rebound: Comparable in Price	Evaluates whether the circular system can achieve a price point comparable to linear alternatives. A higher score suggests that the proposed solution is economically viable and accessible.	Poor rebound mitigation for price. Significant price issues compared to linear alternatives.	Moderate rebound mitigation for price. Shows some effort but price concerns remain.	Good rebound mitigation for price. Offers a competitive price compared to linear alternatives.	Excellent rebound mitigation for price. Maintains or reduces prices, ensuring economic competitiveness.	0
	Total Score					0

Fig. B1. Scoring sheet with judging rubrics.

Appendix C. Workshop feedback

(Fig. C1).

Topic of Feedback	Expert	Quote
General	7	Okay. So, first of all, let's say that I really like your approach. So, really well done. I like that, you structured the different phases and you like everything. It's pretty clear that it's awesome because sometimes, I mean, it's difficult to me. It's like it's really clear because there are so many things that you want integrated. And, I think you integrated almost everything, and but still, it is pretty clear. So, really well done. So from me, what I also like is that you have, like, distractions and then, clear example of how to, to implement what, like, like an example of what, the user should do necessarily. Good.
	7	What is also confused me is like, there is no, like, a time frame. Because like, I'm like, yeah, if I have like three weeks to understand that, it's one thing, but if I have like two hours, it's another thing.
	3	Yeah. Perhaps it would be nice to have some examples in the system as well. Not maybe in the in the knowledge base, but maybe in the beginning or perhaps some examples like these are circular products. They these steps. So use your tool for already existing products to see. If it fits your system and if it could be an example for it. But it would be nice to to see how others are doing it.
	3	for now, what I said I. I'm always better in looking at it in my own time, and then see if you can find things that you or you should do different. But I guess I think it's already. Quite pro system, which is nice. And as you said, there's so much you want to put in. But you also need to make it a bit easier for beginner. Yeah. I currently don't have a project for it, but otherwise I would love to try it to see if I could use the, the projects that are coming up to see how the system would work on my own.
	10	Well, because I do think I see this as a good, guide, but if you just gave it to me like that, I don't know if I would have immediately follow the same way you. You showed it to me, right? Like I would have gotten left to right instead of left. Right down the next step. And then iteration.
	8	Yes, but I think I'm sure it will go well. And also, maybe what helps. It's to define a lot like the type of audience that you have. So you don't frustrate a lot like, okay, so who are we designing this for. And it's that level of knowledge because it's like oh it's an advanced tool. Then of course people that have been in this for many, they will, they might criticize so much. But like if we say now actually this tool is for people that want to get started, then make sure that the ones that try. They are that type of profile. That something that I could have learned. I, I learned from past.
	1	No, it's really. It's really well done. I can really again. I mean, I don't know if you're thinking about it already, but I think they should be. This should be, a software.

Fig. C1. Summary of workshop feedback.

System **Research**	3	You know, so your focus is not really on materials, right? Because that could be your starting point as well. I started in October as a research facility for materials for bio based materials and that now I noticed that that is a very interesting, starting point since these new materials for circularity, not only designing for recycling or designing for. Lasting products or designing for biodegradable products. It's very interesting to start from a material perspective as well, since that, because we're always trying to look for, replacing other products or to current products for circular products. But. Some materials can't be replaced. So we are looking into new materials that have a different approach that have a different specifics, which we can't use in the current way.
	3	And I think otherwise my feedback here would just be that I imagine it would be difficult if someone went in without a concrete product or service. So this ear, so static finished product. The second part because, um, I understand why is in there but have. I can imagine that it's honestly super difficult for people to somehow come to a result and also much broader if you just say, we have the product, we want to change it and then I'll go with you and identify potential.
	6	Perhaps I would even say not the product, but the service itself.
	6	And there would perhaps be considerations where you then say okay, where are with this system map or with the with the. What about the supply chain mapping or something like that, where you then say In this service that we offer, there are perhaps things in places that are not so cheap. And that you can then, so to speak. Find out products. Or, or, or. And then it is to this testing product. First it lands. Um. I could imagine that.
	3	Those. That's. It makes sense that you. Start by research. And I think it's good that you also have, complementary tools because. It's always nice to see how others are doing it, and other tools using tools to get more in depth.
	4	Yes I think. You should. Implement a sort of a toolbox where you have the component. That might be used to get depravity out there. So to me, it's my experience. I think it's very difficult starting from an existing product and getting the same type of or similar type of problem. With circular com. Yeah, the point is you need to start to think. Hair color. Before starting to imagine this day something. But just to give you an, on the an example of the experience I had in the upper industry, what's happening in the apparel industry at Design of Design a product. And then he tries to embed some sustainability circularity. So they say, okay, let's use that. We like this type of product. Let's use that recycled fabric to make this type of product. Or let's try to make now this type of product. In a single type of material, so it can be then recycled because of the character of the defect that we see. Actually, no one of this system at the end was working properly. The only, the only solution I can see is that you start to think circular and then you start the design.
	8	I mean, I think the steps are fantastic. When you were running me through the first, with, brain was like, is there any step that includes, going into the future and doing a bit of foresight? But I can see that here. There's a bit of that, like formulating a vision.
	8	Yeah, I think it makes sense. And it's, useful that you divide it also in, in, a visual way for people to. Have more clarity on where they should aim to focus.

Fig. C1. (*continued*).

	2	Maybe another thing to consider, which you have considered in certain parts. Is also. The connection to place. And I think you did like with the infrastructure. But maybe I can also imagine a place in terms of environmental consideration that could be, something cool. Because sometimes I believe that, circulatory system maybe do happen in the uniqueness of a place, which is kind of something cool to consider. I don't know how they, they call it, but now. But it's kind of like this interspecies, like systems, essentially. So is that. Not. So maybe something around culture will be cool. Like. Certain system research on on on cultural. Cultural boundaries also. Like? Yeah. That's the only two thing that I was thinking, but the rest is is great. I really liked that. Each box then gives you. Like some some ideas of, how to look into it, like the legislation, looking at the different ones. Yeah, that's that's the comments that I have.
	1	So there exists something here which I'm sure you've come across, which is called systems mapping. And this is what we do at the beginning as well. So they already have really nice. A nice framework and tools to do this, which, you can draw from if you haven't already. Just in terms of like the approach of doing the systems research or systems mapping. So what we usually use is one of two. Well, actually there's there's more, but we use two specific ones called the cluster map. And process mapping. The. Cluster map is really nice because it's basically like a. Brainstorm. Bubble.
	2	maybe just from, from my point of view. Is the fact that. Kind of maybe between between the system, the system research and the business model there. There is, in my opinion, a possibility to. Yeah. To kind of create create your project, create your system just by essentially creating these bridges. Like especially if you're doing the system research, connect it to a specific. Please. There's definitely a lot of, a lot of possibilities that can come in because already, if I say, I don't know, I see. Technological enablers, b being AI infrastructure, material properties. In one thing you might connected the two and you have. I don't know, a product or a service that you did in. Think about. Right? And I feel like it's really. The point is really thinking of the the product or the service that you're creating as this. Thing that creates this new system. And in fact, it, puts it into reality, essentially. And after you do that, then you kind of can consider. Business models that will work for this. I really like the visualization of the system because I think it can enable also. The creation of new business models in a sense. I really like that. I think is really cool. Exactly. Because like Jen said. There might be business models that do not exist yet. Exactly, because we don't live in a circular economy. And then. Yeah, at the end, the USS both. If the the product and service that you made that really. Works in the in the vision of the system essentially. And the bees and the experimentation and the evaluation of the business model. I think this is really cool and and I really like that. You guys have done a lot of good. Yeah. Framework building for, for this. I like it. So is this these four steps, right. All the all the things that were around are just like notes and things that this like and this, for example.
	1	And you take in consideration all of these different parts that you have researching the system. So technology, culture, environment, like all of these different moving parts. So we, we usually do in this sort of what if statement. Which is kind of easy and it's more open than. A problem statement. We are really against like the idea of problem solving in that sense, because problem solving, in our opinion, kind of perpetuates bad systems.

Fig. C1. (*continued*).

	4	Yeah. Because, you know, I think we should as well maybe start to think. We are thinking to the to be circularity with quite the holistic approach. But at the end of the day, these circularity or distinctions that are working as well, they In this moment, I am just brainstorming. They are they are working based on the how could they state? Let's call it local situation. Imagine legislation, for example. You like. Yeah. Imagine like yeah. The the infrastructure to collecting the waste. So I think as well these you should try to. Let's say make this as one of the crucial points on the analysis.
Life Cycle Thinking	7	So then I see the, the. Next phase in this column, the one where you define the different life cycles, if it makes sense to have it in the previous one, because here it's more like. We are not defining how many life cycles you want here. You are defining if this is feasible or not, isn't it?
	6	I would. I would rather bring in user journey mapping or something like that. Or maybe a service blueprint. So if it's really about services, where you can really see. If we say there is already this good sharing business, that you say okay, let's map this entire business or the entire service, then you have such a service blueprint, where you can see others with front stage backstage, what is needed in this and in this service, what is needed to perform this service in the end. Because I believe that you could then lead various points that you could then somehow include in this assessment. Which you then take further. So instead of taking a product, you somehow take these three four components further.
	6	Yes, because I think what I've seen is often really lacking in that inspiration. So what can you actually do? And um. And I think that could and and then also. I think these example cases also help. That you. That you show people. Hi. Okay, the company has Netflix, for example. Okay, Netflix 01. three. There are already models. Um, what if your product somehow worked in a similar way to Netflix or Access, similar to Netflix? Well, exactly, that you simply take a bit. Provide a bit of inspiration from existing cases. But as I said, I thought it was cool that you go through this. So that she says that it's greener, which he should start with, and then it just keeps going down.
	3	But it's nice that you think about this like several life cycles, but I because I did some courses just to see what they were trying to explain, and maybe they could teach me more, but they always explain about life cycles, but they never showcase several in one visual. So that's nice that you added that.
	10	Yeah. Well, yeah, because I see I can see this, especially if you're doing multiple life cycles, like really detailed. It can take a lot of time, right? If you're doing the research for each of those different life cycles, with different strategies even.
	10	You know, like the what you mentioned, you know, the the logic behind it makes a lot of sense. And, and you cover one of my blind spots, which is, you know, kind of starting to look at the business models.
	4	No. I really like the idea of having this kind of green, yellow, red. Yeah, I think it's. Very, let's say, useful.
	5	I mean, while designing your product, it's, always nice to have a little bit some insights of, of, which option is more. Sustainable in, in terms of, of LCA. So. Yeah, I mean, that's up to you, but maybe it could be interesting to add just some very rough data or some very rough information on them. Yeah. On the on the materials you use or on the on the production techniques or.

Fig. C1. (*continued*).

System Creation	7	What if like if a I find complicated is the phase three to be honest because you have so many things. There. So that can be yeah, it can be overwhelmed. So basically I would simplify this. This column to be honest. Maybe you can just like. You can just like find a simplified version of the business model to canvas or like even create, your own business model canvas with just like. 3 or 4 boxes.
	4	They seem to me the the most. The crucial point is to try to understand if your product can be circular is the first thing that I think. You need to look at is the take back system. Yeah. Or taking back possibilities.
	4	Yeah. Because, at the end, and again here, I'm just brainstorming to get circularity comes in play. You need to have a network. It cannot be. So idea. Yeah. So it can be just the initiative of one. It has to be a sort of collaborative action. So this is as well, another one thing that needs to be, I think, highlighted since the beginning.
	8	And in this area of step three, I would say that it's not just about if it's too expensive for you or if the logistics are more complex for you. So some rebound effects or unintended consequences, I would say look inside to the business, but you need to look outside the business at many different scopes, and on many different timelines to understand if your decisions are creating, like really bad systemic. Situations or other actors that are players. Or maybe they are just not players of this project. In the short, medium and long term.
System Fit	7	So what I would suggest, because this is designed for execs like that, tons of different threads where I would suggest if you want to just detail a little bit better, your design strategy, maybe it is. Well, to just define what kind of strategies like for instance, it can be designed for disassembling and reassembling, designing for, repairing, designing for. So just like give some specific example that are really generic. And then, just to define a little bit better, but not in the data. Okay. And still like. You can also use like a box where people can just take things and just to tune faster the the process because I think like. You want to come up with an idea as possible and test it as soon as possible? You cannot spend, like, years in developing it.
	7	Maybe doing a asking questions element. This is just, an idea. Maybe you can just ask him a question if you are and the materials that you, you intend to use, toxic or not? Yes. Not. And then ask, like, I don't know, I would, I would structure it in a way that. Because this is very, broad and generic, but I would make a little bit more specific so that it's. Of course, this depends also on how much time do you have to develop this?
	3	So where can you can you show me again where the material part is? Like, you had two steps, right? It was in the life cycle or. Yeah, yeah. Because a good example is, for example. Yeah, I probably don't know it, but in Holland you have Peter Paul's. And, you know, he took the bitter pot. So it's a sort of, supermarket that will bring you your, your groceries. But they they bring it in a glass pot. And. They replace your glass pot for the new groceries and so on and so on and so on. And they did a life cycle assessment on the material. What kind of material to use? Because glass is not that great. It doesn't have a good CO2 footprint. And they came up with an LCA that they at least needed to use it 3 or 5 times. And then it would be good, good material. So they they did lifecycle assessments on glass, on plastics, on, on, ceramics. And in the end glass came out. But it was a really big. Feature in their design process because they really needed to add their, change their strategy in order to make glass a good material. And also because for most people, glass, is a sustainable material. So they

Fig. C1. (*continued*).

		considered the, not only the CO2 footprint, but also the, consumers behavior, as you explained in your, system as well. And they also considered. The way they would use it. Because glass bottles fall apart if you turn around or. So material could be is a really, really big topic in most design processes, especially when you use the LCS and. Design your strategy. Yeah. So perhaps you already have a step. Back to your system, right? If you knew already, you knew you could.
System Evaluation	7	I understand you want to do the LCA, but in general terms I'm really against that. In, I mean, with that, that, although the LCA should be run at the, you can run a simplified version of LCA, but then it's like when you already have your, like you, you did prototypes because you need to understand like technical and technical things, like from where you are going to buy your materials, so that it's really detailed, even if you use the simplified version, but that. Yeah. So is that what you want me to have, like as you really detailed final product or not? So in that case it makes sense to have LCA or if you want just the media and then test it with users and then like. Better reframe it. After that. The test, then. I don't know if now you need the LCA.
	3	Well, actually the entire two I think. Okay. That's good. And then and then it it really helps you to develop a good product. And then you trying to evaluate it yourself by sort of, filling in and LCA, which also gives feedback for the rest of the system. So I understand you edit but, I'm just wondering if that would. Give you the confidence that it is. But the LCA is incomplete because you need to consider so many things for an LCA. So I'm wondering if that in the end you're, you're skipping something and then you just we'll say as a, as a beginner. Okay. So I have a good product and let's continue and, and then start a new project and do the entire two again. And then my final my final result is good again okay. Let's continue with this LCA is a yeah it's a big topic in this circle world and also is a really difficult two that if you ask three people to make an LCA, three people get different results. Yeah. Yeah.
	4	Why don't you why don't you, for example, make this in the most simple? Because I agree with you. LCA is really complicated. You need, even to have some that even on my case, they explain me 2 or 3 times how LCA it works. But nowadays I still, I don't remember, I think. Yeah. Why don't you focus? Don't you decide to focus only instead of LCA, for example? Just the CO2 emission.

Fig. C1. (*continued*).

Appendix D. Circular Systems Sandbox

(Fig. D1).

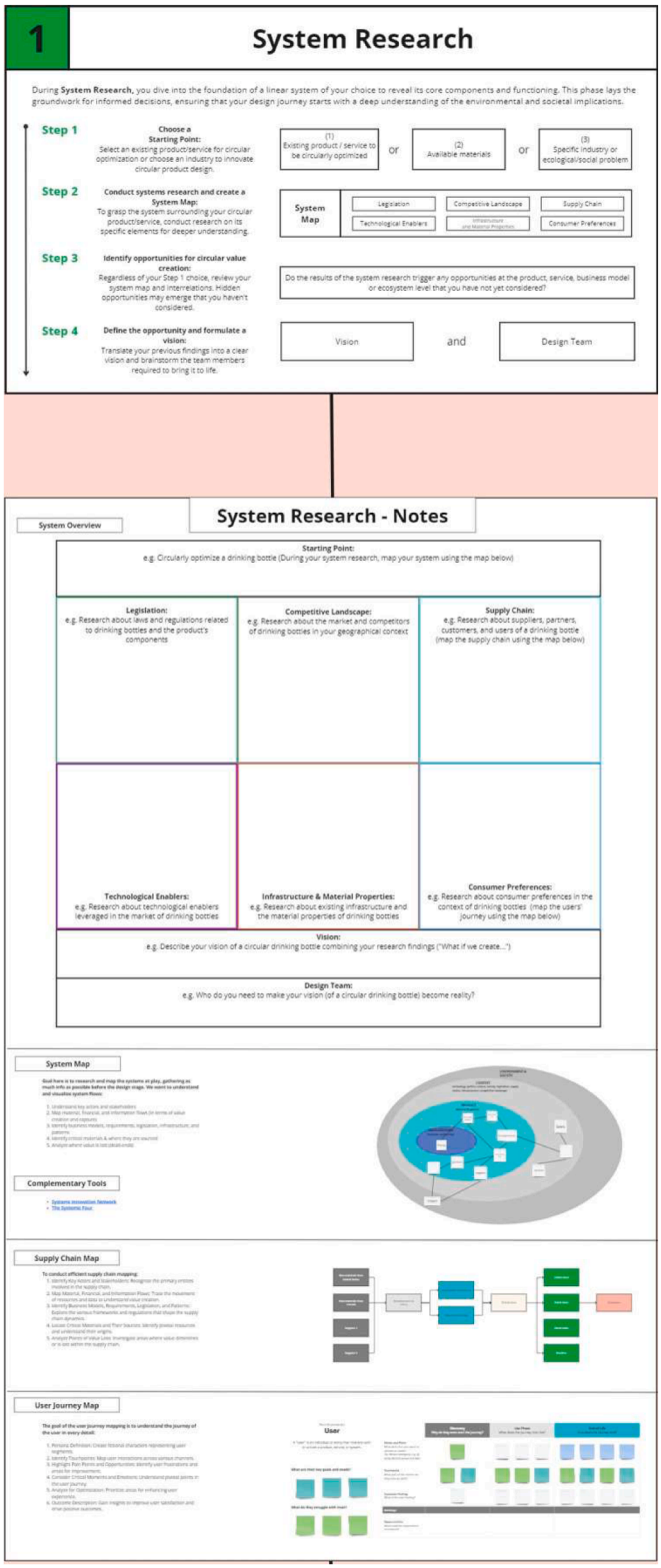


Fig. D1. The circular systems sandbox – A process tool for the design of circular systems.

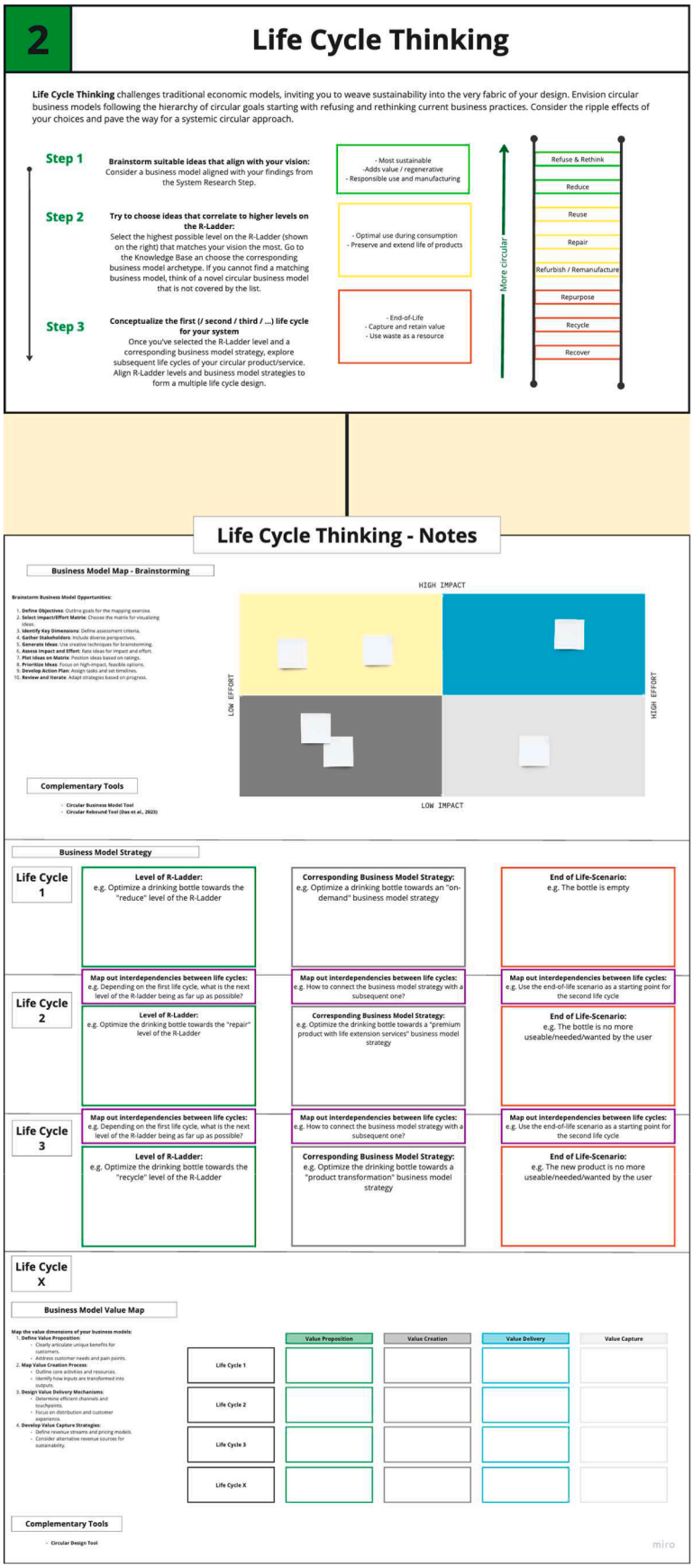


Fig. D1. (*continued*).

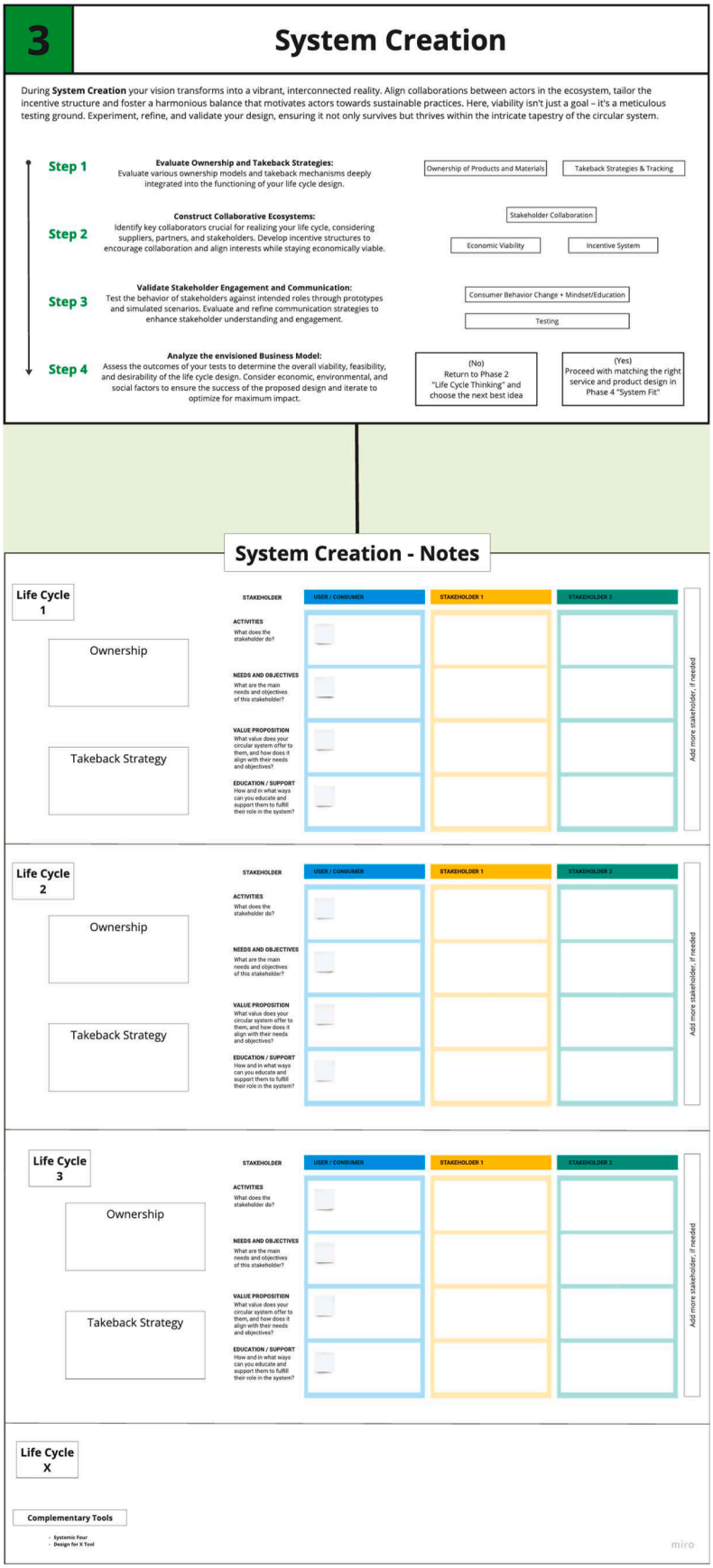


Fig. D1. (*continued*).

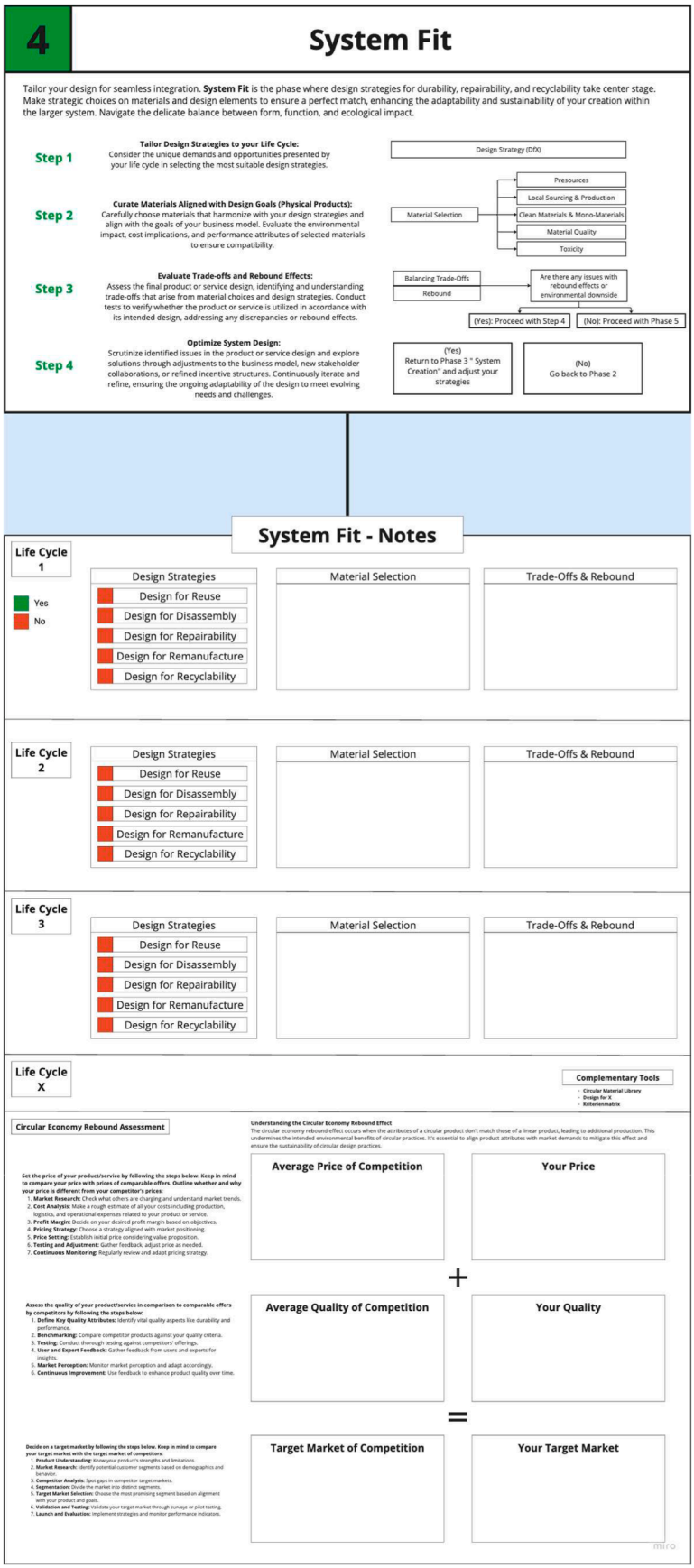


Fig. D1. (*continued*).

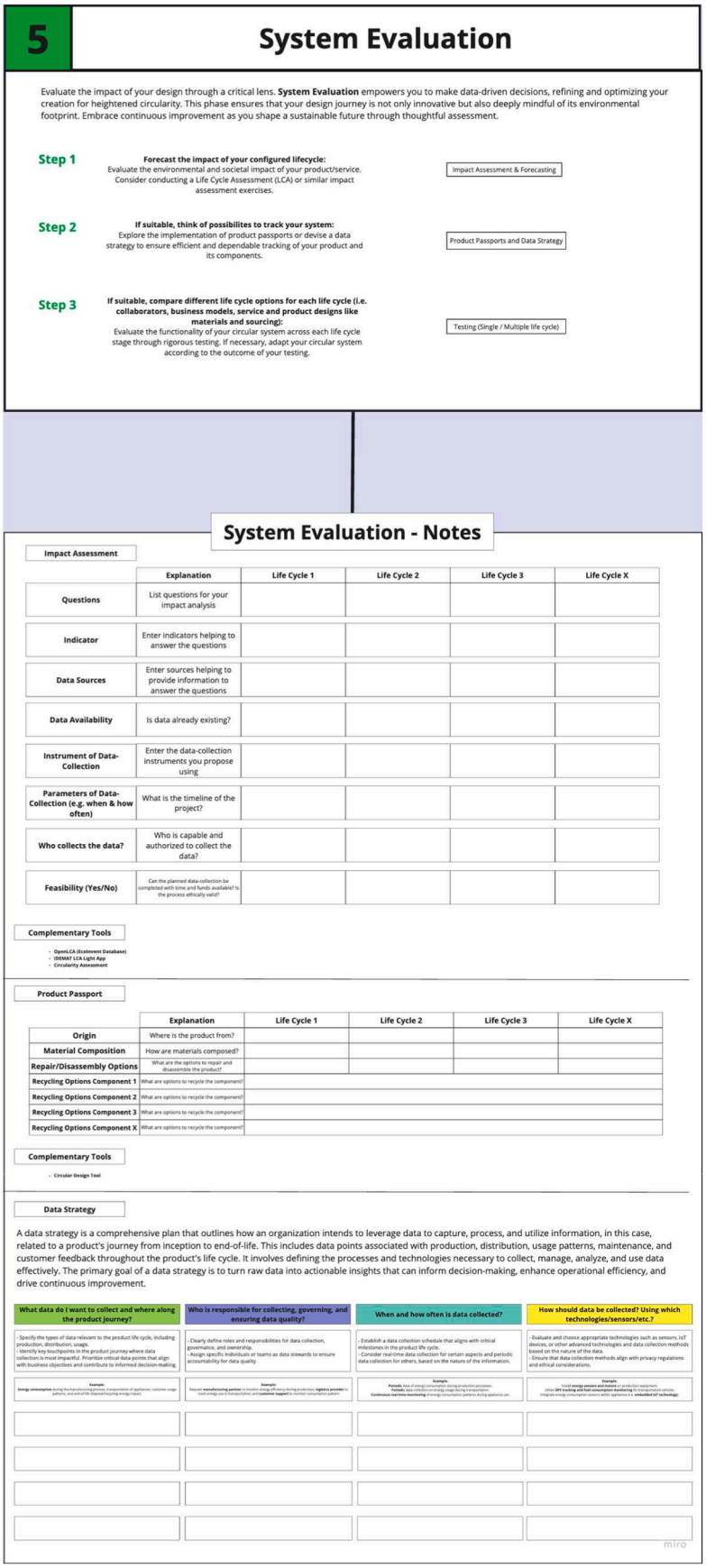


Fig. D1. (*continued*).

Data availability

Data will be made available on request.

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