MAKING THEORY WORK

Bridging the gap between environmental sustainability assessment and circular design practice

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bridging the gap between environmental sustainability assessment and circular design practice

By

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EXECUTIVE SUMMARY

This research addresses the urgent need for effective environmental sustainability assessments that can be seamlessly integrated into the early stages of the design process. Designers have the potential to influence up to 80% of a product's environmental impact; however, they often face challenges in incorporating environmental assessments at the outset of a project. Furthermore, traditional linear production models contribute significantly to environmental issues such as resource depletion and pollution. The Circular Economy (CE) presents a promising alternative by aiming to close resource loops and reduce waste. Nevertheless, integrating CE principles does not inherently ensure environmental sustainability due to potential unintended effects like the "CE rebound." This highlights the critical need for advanced assessment tools that can accurately evaluate the environmental impacts of circular designs.

The primary objective of this study was to establish the requirements for an early-stage quantitative assessment tool that integrates Life Cycle Assessment (LCA) into circular design processes. The research aimed to determine how LCA can be effectively incorporated into early decision-making stages, identify suitable methods for evaluating circular design strategies, assess the usability of existing LCA tools, and address the challenges designers encounter when implementing environmental sustainability assessments.

The research was conducted in three phases. The first phase involved a detailed examination of designers' decision-making workflows. In the second phase, existing sustainability assessment methods and LCA tools were evaluated. The third phase focused on developing a program of requirements for a new assessment tool. Methodologies included comprehensive literature reviews, analysis of grey literature, interviews with experts in environmentally sustainable design, and usability testing of existing tools.

Key findings revealed a significant gap between the complexity of existing LCA tools and the practical needs of designers in early design phases. Current tools are often either too complex or overly simplistic, failing to accommodate the iterative and creative nature of early design processes. Designers typically rely on intuitive methods that are not well-supported by traditional LCA tools, which are data-intensive and complex. To bridge this gap, the study developed a program of requirements for a new tool featuring a dual-interface system: one interface tailored for designers to streamline integration with creative workflows, and another for sustainability experts to manage detailed modeling and scenario analysis. The proposed tool also emphasizes the incorporation of ex-ante LCA for predictive analysis, enabling designers to evaluate products in development and perform scenario analyses based on estimated data. Additionally, integrating qualitative assessments alongside quantitative data will provide a more

comprehensive evaluation of circular design strategies. This holistic approach aims to align LCA tools with designers' practical needs, enhancing the integration of environmental sustainability into early-stage product design.

Recommendations for future development include:

- Developing designer-friendly LCA interfaces that simplify tools and align with designers' workflows.
- Enhancing the environmental sustainability assessment of circular design strategies by improving tools to evaluate products across multiple life cycles and qualitative evaluations.
- Incorporating the ex-ante LCA approach to enable early-stage assessment and scenario modelling.
- Creating actionable interfaces that offer clear guidance and visual aids for result interpretation and decision-making.
- Enabling collaboration between academia, governance, industry, and tool developers to ensure that tools meet both research advancements and practical industry needs.

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LIST OF ABBREVIATIONS

AI	-	Artificial Intelligence
BOM	-	Bill of Materials
CAD	-	Computer-aided Modeling
CE	-	Circular Economy
CSDP	-	Checklist Sustainable Product Development
CSRD	-	Corporate Sustainability Reporting Directive
CTC	-	Cradle-to-Cradle
CTI	-	Circularity Transitions Indicators
DfE	-	Design for the Environment
DfX	-	Design for 'X'
DPP	-	Digital Product Passport
EOL	-	End-of-Life
EPSM	-	Environmental Performance Strategy Map
ERPA	-	Environmentally responsible Product/Process Assessment
EU	-	European Union
GHG	-	Greenhouse gas
IE	-	Industrial Ecology
LCA	-	Life Cycle Assessment
LCD	-	Life Cycle Function Deployment (LFD)
LCP	-	Life Cycle Planning
LCT	-	Life Cycle Thinking
LiDs	-	Life Cycle Design Strategies
MECO	-	Material, Energy, Chemical, Other
MET	-	Material, Energy and Toxicity

MFA	-	Material Flow Analysis
ML	-	Machine Learning
PEF	-	Product Environmental Footprint
PCF	-	Product Carbon Footprint
SMEs	-	Small and Medium-sized enterprises
Sub-RQ	-	Sub-research question
TRIZ	-	Theory of Inventive Problem Solving
QFD	-	Quality Function Deployment

1.

INTRODUCTION

The current state of the Earth's environment is defined by a multitude of critical environmental concerns that have caused humanity to transgress its planetary boundaries. The loss of biodiversity, pollution of water, air, and soil, resource depletion, and overuse of land collectively endanger the planet's life support systems (Steffen et al., 2015). These issues are driven by population growth and societal habits related to production, consumption, and disposal, which can be broadly characterized as the take-make-dispose approach (Ellen MacArthur Foundation, 2013) The environmental consequences of this so-called linear economic model is becoming increasingly apparent, creating an urgent need for sustainable alternatives.

In response to these challenges, the concept of the circular economy (CE) has emerged as a potential solution. The CE aims to transition from the linear take-make-dispose approach to an economy where waste is regarded as a resource, thereby establishing a closed-loop system. This model emphasizes the continuous reuse and regeneration of resources while minimizing waste. The European Union (EU) has adopted the CE as a means of decoupling economic growth from resource use, protecting natural resources, and boosting sustainable growth by reducing consumption and increasing circular material use (European Commission, 2020a).

Designers have a central role in this transition, as their choices significantly influence the environmental outcome of a product. The Ellen MacArthur Foundation (2022) notes that the design process accounts for up to 80% of a product's environmental impact. In light of these considerations, the EU's Circular Economy Action Plan includes both legislative and non-legislative measures, emphasizing the design phase across the entire product lifecycle (European Commission, 2020b)

To address these issues, design approaches focusing on environmental sustainability and circularity have emerged, along with various methods and tools to assess the environmental sustainability of a product. However, integrating the CE framework in design does not necessarily guarantee environmental sustainability. CE can lead to unintended consequences, such as the 'CE rebound' effect, where the expected environmental benefits of circular strategies result in increased overall production, thereby reducing their net positive impact (Zink & Geyer, 2017). Furthermore, the environmental impacts of circular design are currently uncertain, and it is unclear how circular products can effectively substitute conventional products in an environmentally sustainable manner (Corvellec et al., 2022; Korhonen et al., 2018). This underscores the necessity for accurate environmental sustainability assessment and guidance throughout the design process to ensure that circular designs genuinely contribute to environmental sustainability.

This thesis seeks to examine how designers can be effectively guided to make environmentally sustainable decisions within the context of circular design. Despite a substantial body of research on methods for guiding environmental decisions of designers (Kristensen & Mosgaard, 2020; Schäfer & Löwer, 2021), the uptake of these approaches remains relatively limited (Peace et al., 2018; Pigosso et al., 2015). Moreover, the environmental sustainability assessment of circular design strategies is still in its early stages and requires further comprehensive investigation to develop a robust toolset for designers (Elia et al., 2017; Kristensen & Mosgaard, 2020; Sumter et al., 2020; van Loon et al., 2021). The objective of this thesis is to establish a foundation for the development of a tool that addresses the needs of designers when conducting an environmental sustainability assessment and to investigate how a tool can effectively guide designers towards environmentally beneficial decisions concerning circular products.

The introduction chapter of this thesis is structured as follows. First, the background is given. This is followed by a statement of the problem and the research aim, presenting the research questions. Subsequently, the relevance of the research is addressed, and finally, the structure of the thesis is outlined.

1.1. BACKGROUND

This section introduces the necessary background on the context of this research: the evolution and concepts of sustainable design, environmental sustainability assessment methods, and relevant policies and initiatives that shape the current policy landscape.

1.1.1. CIRCULARITY AND ENVIRONMENTAL SUSTAINABILITY IN DESIGN

The field of environmentally sustainable design has undergone significant developments over the past few decades. The concept of Green Design first emerged in the 1970s with the objective of reducing the environmental impact of products through redesign and material selection (Ceschin & Gaziulusoy, 2016) In the 1980s, this approach was succeeded by eco-design, which adopted a life-cycle perspective, emphasizing the reduction of resource consumption and environmental impacts throughout a product's life cycle (Hanes-Gadd et al., 2023). Eco-design methods identify the aspects with the greatest environmental impact, thereby providing strategic information to inform improvements to designs. It remains a field of design that is actively practiced to this day (Ceschin & Gaziulusoy, 2016). The latest research in eco-design has served to reinforce existing knowledge and tools, while simultaneously extending the scope of the field to encompass organizational and strategic implementation issues (Pigosso et al., 2015).

As the field progressed, the concept of sustainable design was expanded to incorporate social considerations, leading to a more integrated approach to sustainability (Ceschin & Gaziulusoy, 2016). This broader perspective encompasses a variety of approaches and strategies collectively known as "Design for X" (DfX), where "X" represents a specific sustainability strategy. For instance, design for remanufacturing, design for longevity, and design for emotional durability.

A more systematic approach is required for circular design in comparison to previous environmentally sustainable design approaches (Moreno et al., 2016). As the CE strives to regenerate and retrieve resources for reuse, it is evident that alterations to product architecture and surrounding elements, including business models, services, consumer behavior and supply chain management, are necessary (Bocken et al., 2023). The concept of circular design has gained significant traction in both industry and academia over the past decade, underscoring the importance of maintaining product value and utility (Neramballi, 2022). This has resulted in the development of a multitude of methods, frameworks, and strategies aimed at facilitating the design of circular products (Shevchenko et al., 2024). One illustrative example is the R-strategies framework, which prioritizes circular strategies such as refuse, reduce, reuse, and repair (Potting et al., 2017) .

This research scope is limited to the environmental considerations in design, therefore excluding economic and social aspects. Consequently, the focus lies on eco-design principles in circular design.

An overview of the sustainable design evolution can be found in **Figure 1.**

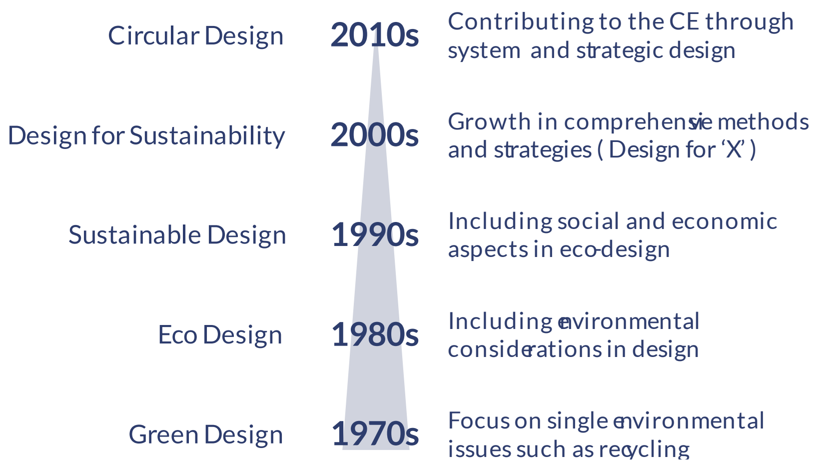


Figure 1. *Evolution of environmental philosophies applied to design. Image adapted from Moreno et al. (2016).*

1.1.2. ENVIRONMENTAL SUSTAINABILITY ASSESSMENT

The standardized eco-design process, ISO 14006 (2020) identifies the second step in a six-step framework as "Environmental sustainability assessment of products". In this step, the primary aim is to identify the lifecycle environmental impacts of products. This standard allows organizations to use a method of their choosing, whether qualitative or quantitative. However, ISO does refer here to the Life Cycle Assessment (LCA) framework. LCA is a prominent method in product development, offering comprehensive insights for decision support on design concepts and facilitate the evaluation of environmental impacts for reporting purposes (Chang et al., 2014; Lagerstedt et al., 2003).

The comprehensive LCA framework quantitatively assesses the environmental impacts of a product throughout its entire life cycle, from the initial extraction of raw materials to the final disposal of the product. The method is comprised of four phases, which have been standardized through ISO 14040 and ISO 14044: goal and scope definition, life cycle inventory, impact assessment, and interpretation (International Organization for Standardization 14040, 2006; International organization for Standardization 14044, 2006), In the initial phase of the LCA study, the goal and scope of the study are defined, along with the functional unit and the impact categories to be considered. The life cycle inventory phase involves the collection of data regarding the inputs and outputs associated with the product system throughout its life cycle. These inputs and outputs may include, for instance, raw materials extracted, electricity, emissions, and waste. In the impact assessment phase, the inventory data is subjected to analysis with a view to evaluating potential environmental impacts across a range of categories (e.g. global warming potential, ozone depletion and acidification). In the final phase, the results are interpreted in the context of the study's initial objectives. This enables the identification of significant issues and the formulation of conclusions and recommendations. It should be noted that each phase of the framework involves iterative adjustments, particularly during the interpretation phase, where findings may prompt a revisit to previous steps to refine data and analysis (Guinée, 2002).

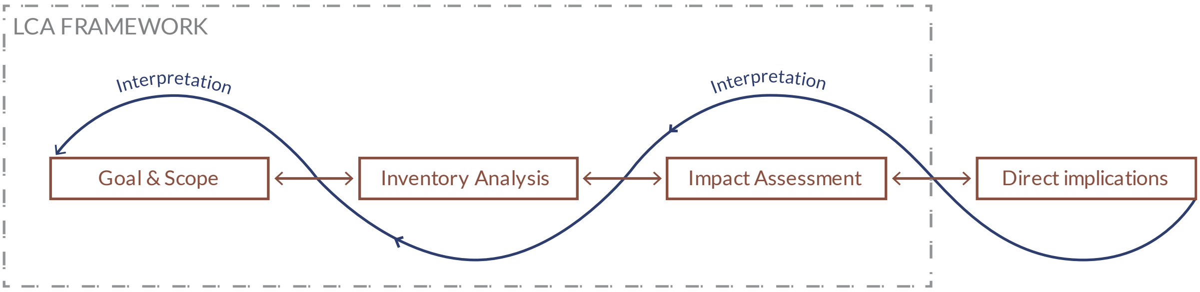


***Figure 2**. LCA framework. Image adapted from PRé Sustainability (2022).*

Recent advancements in LCA, including anticipatory LCA, prospective LCA, and ex-ante LCA, focus on future-oriented scenarios, particularly during early design phases where outcomes are uncertain. For instance, ex-ante LCA is employed to assess emerging technologies at early research and development stages, modeling their potential long-term impacts to support environmentally conscious decision-making (Cucurachi et al., 2018; Guinée et al., 2018; Roes & Patel, 2011; Schrijvers et al., 2014).

Environmental sustainability assessment methods extend beyond LCA to include material flow analysis (MFA), which quantifies stocks, flows, inputs, and losses of resources. MFA is particularly useful in the context of the CE, where it helps to monitor resource use and circularity at both macro and micro levels (Böckin et al., 2020; Graedel & Lifset, 2015; Moraga et al., 2019).

1.1.3. RELATED POLICIES AND INITIATIVES

Policy plays a crucial role in promoting the production of circular and environmentally sustainable products by providing businesses with the necessary incentives for transition. Recent policies and regulations aim to guide companies in assessing environmental impacts and adopting sustainable practices, supporting the European Green Deal's goal of a climate-neutral, resource-efficient, and competitive economy by 2050 (European Commission, 2020b)

A significant initiative is the Circular Economy (CE) Action Plan by the EU, which seeks to establish sustainable products, services, and business models as standards while phasing out waste. It expands the Eco-design framework to cover a wide range of products, facilitating their transition towards circularity. Key aspects include developing a common data space for value chains through mandatory digital product passport (DPP) (European Commission, 2020b, 2024). Additionally, the CE Action Plan emphasizes systematically analyzing the impact of circularity on climate change mitigation and adaptation. Regulatory incentives, such as the Corporate Sustainability Reporting Directive (CSRD), mandate large organizations to report on social and environmental performance, including greenhouse gas emissions and resource use (European Commission, 2022).

The Horizon 2020 initiative, an EU research and innovation program, also has played a pivotal role in promoting sustainable practices. Which researches the application of quantitative methods such as LCA to support the development of environmentally sustainable technologies (European Commission, 2017). To standardize the LCA process, the EU initiated an approach for the impact assessment phase, namely Product Environmental Footprint (PEF) (European Commission, 2021). This program, alongside other EU focused programs such as the EU taxonomy, incentivizes companies to invest in research and development that aligns with environmental sustainability goals.

1.2. PROBLEM STATEMENT AND KNOWLEDGE GAP

Integrating LCA into the design process offers valuable environmental insights but faces significant barriers, including the Collingridge Dilemma (1980), which highlights the challenge of predicting environmental impacts early when changes are still feasible. Once these impacts become clear, it is often too late to alter design decisions, underscoring the need for early-stage LCA integration, see **Figure 3.** However, early LCA implementation is hindered by limited knowledge and data (Matthews et al., 2019) and by the low usability and misalignment of existing tools with the design process (Rio et al., 2011; Saidani et al., 2021; Schäfer & Löwer, 2021).

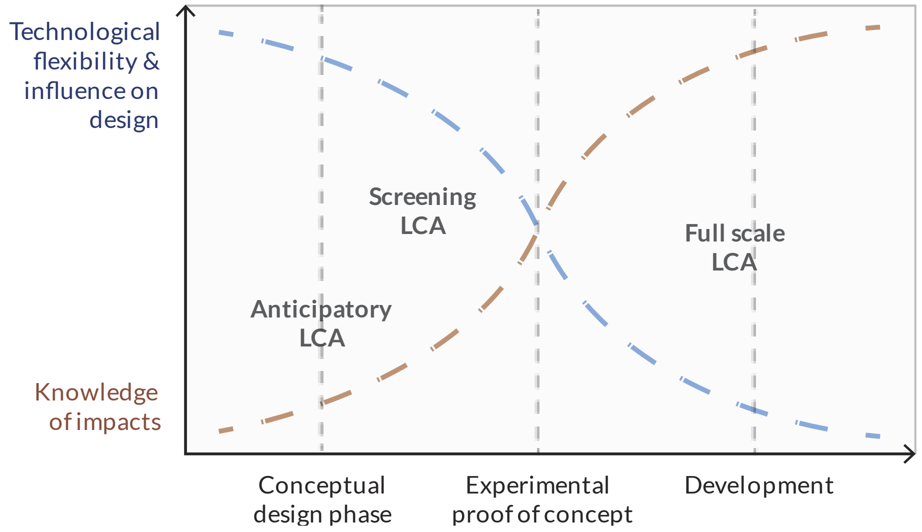


Figure 3*. The Collingridge Dilemma. Image adapted from Matthews et al. (2019).*

Recent advances like anticipatory, ex-ante, and prospective LCA address these challenges by using assumptions and projections to manage uncertainty (Arvidsson et al., 2018; Cucurachi et al., 2018; Schäfer & Löwer, 2021; van der Giesen et al., 2020). Simplified approaches, such as screening and streamlined LCA, aim to improve usability by reducing complexity through assumptions instead of extensive data collection (McAloone & Pigosso, 2017). Despite these improvements and the emergence of over 600 eco-design methods, industry uptake remains low (Peace et al., 2018; Pigosso et al., 2015; Schäfer & Löwer, 2021). The fragmented and varied nature of eco-design methods, which often focus on specific life-cycle stages, products, or industries, limits their practical application in professional design practice. Therefore, companies often struggle with implementing environmental sustainability (Peace et al., 2018; Pigosso et al., 2015). Multiple efforts have been made to improve their application and usability (e.g. Rio et al., 2019; Vögtlander, 2010) which have not significantly increased their adoption in the industry (Willskytt & Brambila-Macias, 2020).

Furthermore, reports on the trade-offs of different CE measures and products are scarce in design tools (Willskytt & Brambila-Macias, 2020). Without a comprehensive understanding, it is challenging to ensure that circular design strategies genuinely succeed in contributing to environmental sustainability. Nevertheless, assessments of the environmental impacts of circular design strategies remain scarce (Spreafico, 2022; Sumter et al., 2020; van Loon et al., 2021).

1.2.1. KNOWLEDGE GAP

Despite numerous efforts to develop effective LCA tools, there is still a lack of comprehensive tools capable of assessing the environmental impact of circular design strategies during the initial stages of the design process. To increase the uptake of the LCA framework in the design field, it is essential to consider the perspective of the designer and their work culture, which has often been overlooked. Lofthouse (2006) emphasizes that industrial designers adopt distinctive approaches to incorporating guidance into their design processes. Furthermore, Collado-Ruiz & Ostad-Ahmad-Ghorabi (2016) conclude that eco-design methods, particularly detailed LCA results, can hinder a designer's creative capacity, leading to design fixation. Consequently, improvements and or developments of LCA tools should be researched while keeping the iterative and creative nature of the design process in mind. To the best of the author's knowledge, the research on how designer's cognition and workflow concerning the problems in the current LCA tools landscape is lacking.

Furthermore, the tool should facilitate the implementation of circular design, which is a primary focus of contemporary designers. Matschewsky et al. (2024) highlights the absence of a practice-centric perspective, which would inform the characteristics of design methods that method developers should consider ensuring their effectiveness among practicing design professionals.

1.3. THESIS AIM AND RESEARCH QUESTIONS

The purpose of this study is to explore and develop the requirements for an early-stage quantitative assessment tool designed to evaluate the environmental impacts of circular product design. Specifically, the aim is to define the requirements for a tool, including the LCA method, that can effectively assess the environmental aspects of circular design strategies at the product level for use by designers within organizations. By defining these requirements, this research aims to lay the groundwork for the creation of an effective tool to support designers in assessing the environmental sustainability of their decisions.

The research focuses on proposing the foundation of a tool that facilitates the analysis of design decisions that could potentially impact the environment. Additionally, it addresses how environmental sustainability assessment could be made accessible and familiar to designers. The proposed tool aims to integrate seamlessly into the early stages of the design workflow, facilitating knowledge of environmental considerations. The overall objective of this research is to contribute to the field of circular design and environmental sustainability assessment.

Research Question

This study is guided by the following main research question: ***How can Life Cycle Assessment be integrated into early-stage decision-making processes for the implementation of circular design strategies?***

To answer this question, five sub-research questions were defined to structure the research:

1. *How do designers make decisions in the early stages of the design process, and how does this relate to environmental sustainability assessment?*
2. *What is the current state of research regarding the utilization of environmental sustainability assessment methods in assessing circular design strategies?*
3. *What environmental sustainability assessment tools, specifically based on LCA, are commonly known and utilized to enable decision-making, and why?*
4. *What challenges do designers encounter when making early-stage decisions on environmental sustainability in the design process, and how could this be improved?*
5. *How could an environmental sustainability assessment tool be designed and structured to facilitate designers in early-stage decision-making on the environmental impacts of circular design strategies?*

1.4. RELEVANCE OF THE THESIS

This research contributes to the scientific community by addressing the gaps in the current methods for assessing environmental impacts within the framework of the CE. By developing the requirements for an early-stage quantitative assessment tool based on LCA, this study enhances our understanding of how circular design strategies can be systematically evaluated. Furthermore, the research seeks to bridge the disconnection between existing LCA tools and the nature of the design process. This research is distinctive in that it draws upon knowledge from both the environmental sustainability assessment field and the design theory domain, combining both perspectives. It advances theoretical and practical knowledge in the field of circular design and environmental sustainability, providing a foundation for further empirical studies and methodological refinements.

This research's societal significance derives from its ability to promote more sustainable production and consumption practices. The suggested approach will assist designers to consider environmental issues early in the product development process, resulting in circular and environmentally sustainable products. This is in line with global environmental goals and circularity aims. Furthermore, by addressing the CE rebound effect, this research promotes more informed and effective implementation of circular strategies, which can ultimately lead to reduced resource depletion, minimized waste, and lower greenhouse gas emissions, thus benefiting society.

From the perspective of Industrial Ecology (IE), this research addresses a critical need for practical tools that facilitate the transition from linear to circular economic models. There is an ongoing development of LCA approaches that are adapted for early-stage decision-making. This research acknowledges this development and makes a step towards possible implementation of these approaches into the design process to provide environmental guidance during the conceptualization phase. Furthermore, this tool can assist companies in integrating sustainable practices into their product development processes, thereby improving their environmental performance and gaining knowledge on resources. This aligns with the principles of Industrial Ecology, which emphasize the optimization of resource flows and the minimization of environmental impacts across product life cycles. Moreover, by proposing a standardized approach to the environmental sustainability assessment of circular strategies, this research can contribute to the establishment of more consistent and comparable environmental sustainability metrics across industries, thereby adding to the field of IE.

1.5. THESIS STRUCTURE

The research approach, detailed in **Chapter 2**, is organized into three phases. The first phase, found in **Chapter 3**, explores the design context. This chapter examines the designer's workflow, role, and behavior. **Chapter 4** presents the second phase of the research. This phase examines the current landscape of different environmental sustainability assessment methods and tools and whether they can assess the environmental impact of circular design strategies. The third phase, found in **Chapter 5**, addresses the findings of the previous two phases by presenting a program of requirements for a new tool. The results of the research are discussed in **Chapter 6**. Finally, **Chapter 7** concludes the research. See **Figure 4** for the research flow diagram.

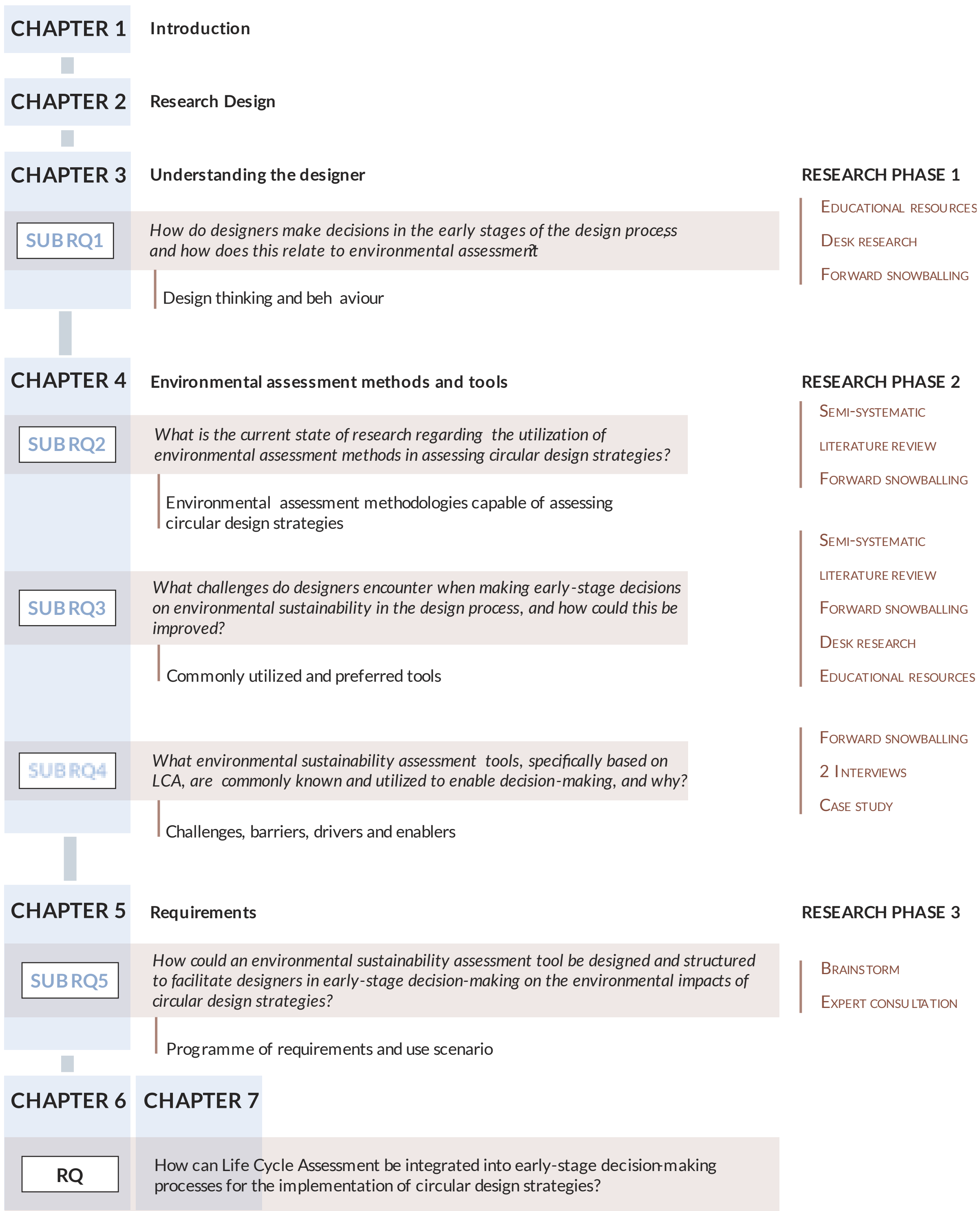


Figure 4. Research Flow Diagram

2.

RESEARCH DESIGN

This chapter presents the research design and methods to gain insights to answer the main research question. The chapter is structured as follows: firstly, the primary research question is addressed; secondly, the terminology utilized throughout the research is outlined; and finally, the research approach is explained in detail for each sub-research question. This chapter aims to provide a comprehensive overview of the research methods used and how the findings were analyzed, see **Figure 4** for a visualization of the research flow.

2.1. OVERVIEW OF THE RESEARCH DESIGN

The research question, "How can Life Cycle Assessment be integrated into early-stage decision-making processes for the implementation of circular design strategies?" is addressed through a research design structured around three phases and five sub-questions, which are presented in **Chapter 1.**

Firstly, the designer's workflow during the early-stage decision-making process of a design project is investigated to gain insight into how designers currently make decisions. The insights presented in this chapter serve as a fundamental element in the research aimed at understanding the workflow of designers, a concept that is repeatedly referenced throughout the research.

Secondly, the selection of environmental sustainability assessment methods and their capacity to assess circular design strategies is examined to identify the most appropriate methods for evaluating circularity. Additionally, the method for selecting relevant LCA-based tools is presented, along with an analysis of their usability, to determine which tools are most effective and user-friendly for designers. The last step in this phase is to understand the challenges, barriers, and drivers surrounding the implementation of circular design in practice are examined to identify factors that influence the adoption of circular design strategies.

Finally, insights from these sub-questions are synthesized to define the requirements and framework for a new tool. This research design ensures that the final requirements of the tool focus on effectively integrating LCA into the early-stage decision-making process, supporting the implementation of circular design strategies, and addressing the main research question.

2.2. TERMINOLOGY AND DEFINITIONS

2.2.1. THE DIFFERENCE BETWEEN METHODS AND TOOLS

This research aims to address the different environmental sustainability assessment methods and tools that facilitate designers making environmentally conscious decisions. To do so, it is important to agree on the definition of what these methods and tools entail before categorizing them in the result section.

In the field of environmental sustainability studies, the terms "methods" and "tools" are often used interchangeably (e.g. Birch et al., 2012; Lindahl & Ekermann, 2013; Rossi et al., 2016). Nevertheless, there is a clear distinction between the two. Environmental sustainability assessment methods encompass a variety of approaches, procedures and frameworks for evaluating the environmental impact of products and processes. In contrast, tools facilitate and streamline the utilization of a method. In the context of environmental sustainability assessments, the term 'tool' refers to an instrument, e.g. software, that facilitates or enhances specific activities or processes. This thesis adheres to this definition, emphasizing tools that support the LCA framework. These include the range of full-scale, streamlined, simplified or screening LCA tools that facilitate the LCA process through various adaptations (Chatty et al., 2021).

2.2.2. CIRCULAR ECONOMY DEFINITION

To assess the circular design strategies that are required in product design, it is first necessary to achieve a universal understanding of what the CE entails and aims to achieve. There are numerous different definitions of the CE (Kirchherr et al., 2018). According to (Lindgreen et al., 2020) a definition should include three principles: value retention, hierarchical waste framework and the aim of contributing to sustainable development. The relationship between sustainable development and the CE is a topic of ongoing debate. Nevertheless, it is frequently cited as the primary objective of the CE (Corona et al., 2019; Kirchherr et al., 2018; Lindgreen et al., 2020). This thesis addresses the interconnectedness between achieving circularity and achieving environmental sustainability. It is therefore of absolute importance that the objective of the CE in contributing to sustainable development is included. The definition of Kirchherr et al. (2018)

acknowledges *this: "A circular economy is defined as an economic system based on business models that replace the 'end-of-life' concept with reducing, recycling and recovering materials in production, distribution and consumption processes. This occurs at the micro-level (products, companies, consumers), meso-level (eco-industrial parks), and macro-level (city, region, nation and beyond). The aim is to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations."* This research adopts this definition and zooms in on the micro-level perspective of CE through the lens of environmental quality.

2.3. RESEARCH APPROACH PER SUB-RESEARCH QUESTION

2.3.1. SUB RESEARCH QUESTION 1

The sub-research question (sub-RQ) addressed here is: *"How do designers make decisions in the early stages of the design process, and how does this relate to environmental sustainability assessment?"* This sub-RQ will function as a lens through which the research will be viewed and will aim to understand the designer's work culture during the early stages of the design process. Answering this research question will be done by researching educational materials and literature on design behavior, design methods and design approaches.

Understanding the Workflow of the Designer

The faculty of Industrial Design Engineering at Delft University of Technology offers a range of educational resources that provide comprehensive descriptions of various design approaches and methods. Two principal resources will be utilized in this study were *"Product Design: Fundamentals and Methods"* by Roozenburg & Eekels (1998) and *"The Delft Design Guide"* by van Boeijen et al. (2013), both published by the university. These resources serve as foundational knowledge for undergraduate students to broaden their understanding of design and its associated methods.

Additionally, the university repository will be used to access further valuable publications that will investigate the design field at a meta-level. This research will focus on "Designing Design" within the industrial design engineering faculty, aiming to gain insight into how designers address complex challenges, such as circularity, during the initial stages of the design process. Two key publications are identified: the dissertation of Daalhuizen (2014) "*Method Usage in Design*", which provided detailed information on design behavior and the use of methods, and Gonçalves & Cash (2021) publication, *"The life cycle of creative ideas: Towards a dual-process theory of ideation,"* which will offer insights into the design process and design cognition.

Besides educational resources, academic sources will also be reviewed to address the research gaps left by the educational sources. This will focus on a more comprehensive understanding of designers' decision-making practices and their approach to early-stage design challenges. For this research, two articles are identified through desk research to facilitate forward snowballing. The first key article is *"Design Thinking, Fast and Slow: A Framework for Kahneman's Dual-System Theory in Design"* by Kannengiesser & Gero (2019). This publication is noteworthy for its integration of Kahneman's dual-system theory with design thinking, thereby providing a vital framework for understanding designers' cognitive processes. The second article is *"Mapping the Conceptual Design Activity of Interdisciplinary Teams"* by Austin et al. (2001). This study explores the initial stages of design projects and the role of interdisciplinary teams, offering valuable insights into the design process.

2.3.2. SUB RESEARCH QUESTION 2

The Sub-RQ addressed is: *"What is the current state of research regarding the utilization of environmental sustainability assessment methods in assessing circular design strategies?"* To answer this, a multi-step approach has been employed.

Selecting Circular Design Strategies

The first aspect of answering sub-RQ 2 is to identify the circular design strategies. These strategies are aligned with the definition of the CE as outlined in **section 2.2.2.** A literature review focusing on circular design will be conducted to identify the most frequently cited articles on this topic. The search query will only include articles that focus on circular design in product design, thus excluding the built environment. The following search query in Scopus will be used: TITLE-ABS-KEY ("circular design strategies" OR "circular strategies" OR "strategies") AND ("circular design")) AND NOT (construction OR demolition OR built). The ten most cited articles will be reviewed to extract and compare circular design strategies.

These strategies will be categorized and clustered to determine which approach best represents the full spectrum of CE principles. Indicators that measure the effectiveness of these strategies will also be defined based on insights from the literature.

Identifying Relevant Environmental sustainability assessment Methods

A semi-systematic literature review will allow for studying broad topics across diverse disciplines (Snyder, 2019). This approach will be chosen due to the extensive literature on environmental sustainability assessment methods in design. The review will follow Snyder's (2019) guidelines: design, conduct, analysis, and structure the review.

The search, conducted on Scopus and Web of Science, will focus on articles from 2010 to May 2024, identifying 76 articles initially. Titles and abstracts will be screened against selection criteria, leading to the inclusion of 32 relevant papers, as detailed in **Table 1**.

Table 1. *Research protocol: sub research question 2.*

Research Protocol	Description
Database	Scopus, web of science
Search Field	Abstract, title keywords
Search String	“Environmental sustainability assessment" OR "environmental sustainability assessment" OR “eco-assessment” OR “circular economy assessment" OR "CE assessment"
	AND
	“Circular design" OR "circular product design" OR "product design" OR "sustainable design" OR "circular strategies" OR "circular economy strategies" OR "CE strategies" OR "product design" OR "product service systems"
	AND NOT
	built OR process OR building OR plant OR refineries OR biorefineries OR construction)
Data Range	2010 until May 2024
Publication Tyoe	Peer-reviewed journals, conference papers and book chapters
Intermediate Result	76 papers
Inclusion Criteria	Articles addressing environmental sustainability assessment methods that are used by design practitioners during decision-making throughout the design process.
Exclusion Criteria	Articles focusing on the development of methods for contexts not related to product development or specific to sectors.
Final Result	32 papers

For further refinement, two key articles, "Measuring circular economy strategies through index methods: a critical analysis" by Elia et al. (2017) and "A taxonomy for eco-design tools for integrating environmental requirements into the product design process" by Bovea & Pérez-Belis (2012), will be used for forward snowballing Wohlin (2014). This process will identify additional relevant literature, resulting in seven more articles.

The review will result in an extensive list of eco-design methods and tools. Each approach will be annotated with details such as its type, whether it is more of a tool or a method, its qualitative or quantitative nature, and its application stage in the design process (see **APPENDIX A**) From this list, 20 methods will be selected based on the following criteria:

- Alignment with the method definition: Methods must conform to the definition from **section 2.2.1,** excluding those considered tools. The methods can be both qualitative and quantitative.
- Life Cycle Thinking (LCT): Methods should evaluate the entire product life cycle, ensuring consistency and compliance with eco-design standards, ISO 14006 (2020)
- Recent relevance: Methods should be evidenced in literature published after 2015 to ensure they are current.

Eco-Design Methods and Their Ability to Evaluate Circular Design Strategies

To evaluate the capability of these eco-design methods, a matrix will be developed. This matrix will cross-reference each method with the identified circular design strategies. Each method will be assessed on its effectiveness in addressing specific aspects of these strategies using a scoring system:

- Yes: The method fully addresses the aspect.
- Partly: The method addresses some aspects but has limitations.
- No: The method does not address the aspect.

This matrix will provide a comprehensive evaluation of how well various environmental sustainability assessment methods can assess circular design strategies, offering insights into their effectiveness and the current state of research in this area.

2.3.3. SUB RESEARCH QUESTION 3

This sub-chapter addresses sub-RQ 3: *"What environmental sustainability assessment tools, specifically based on LCA, are commonly known and utilized to enable decision-making, and why?"* This question has three aspects: identifying commonly used tools, examining which are frequently referred to in design research and how interface and modeling aspects of a tool influence its usability.

Identifying Commonly Used Tools

To address the first part of Sub-RQ 3, a comprehensive list of environmental sustainability assessment tools will be compiled through a multi-step process. Initially, a semi-systematic literature review will be conducted, utilizing the search terms from **section 2.3.2.,** with an added focus on tools and early assessments. The review will involve the keywords “early” and “tools” to refine the list.

Table 2. *Research protocol: sub research question 3.*

Research Protocol	Description
Database	Scopus, web of science
Search Field	Abstract, title keywords
Search String	“Environmental sustainability assessment" or "environmental sustainability assessment" or eco-assessment”
	AND
	“Circular design" OR "circular product design" OR "product design" OR "sustainable design” OR "product service systems"
	AND tools AND early
	AND NOT
	Built OR building OR plant OR refineries OR biorefineries OR construction)
Data Range	2010 until May 2024
Publication Type	Peer reviewed journals, conference papers and book chapters
Intermediate Result	11 papers
Inclusion Criteria	Articles addressing environmental tools that are used by design practitioners during decision-making throughout the design process.
Exclusion Criteria	Articles focusing on the development of tools for contexts not related to product development or specific product groups.
Final Result	7 papers

In addition to the literature review, grey literature, including company reports will be examined. This search will involve using Google with the following terms: [LCA OR "simplified LCA" OR "streamlined LCA" OR "screening LCA" OR "environmental CAD"] AND tool AND "product design”, to identify relevant tools.

Relevant papers will also guide the research. Specifically, *"Review of eco-design methods and tools: Barriers and strategies for effective implementation in industrial companies"* by Rossi et al. (2016) and *"Analysis of environmental sustainability methods for use earlier in the product lifecycle"* by Brundage et al. (2018) will be used. Forward snowballing from these papers will help find additional tools.

Through recommendations and research in the design curriculum of Industrial Design Engineering at Delft University of Technology, several tools are identified that support and guide the development of environmentally sustainable products. The following tools will be included in the research:

- EcoSketch (Chatty et al., 2024)
- Footprint CALC (The Footprinters, 2024)
- Idemat Light LCA app (Muersing & Vogtländer, 2024)
- Fast track LCA teaching tool (de Groot, 2023)

From this extensive list of tools, criteria are used for refining the list of potential environmental sustainability assessment tools. These criteria are based on the alignment with the research question, which focuses on identifying commonly known and utilized tools based on LCA and understanding their role in providing decision support. Each criterion ensures that the selected tools are relevant to the research.

The criteria will be the following:

1. Product or service-oriented: Tools should be primarily focused on assessing the environmental impacts of products or services.
2. Decision support: Tools should be designed to support decision-making during the design process.
3. Availability and Accessibility: Sufficient literature should be available to understand the capabilities and limitations of the tool. The tools that have a cost barrier should be able to be understood through the demo versions.
4. Applicability in the early design phase: Tools should be suitable for use in the early stages of design when significant environmental decisions are being made.
5. Primary LCA focus: The primary purpose of the tool should be environmental sustainability assessment, although additional functionality may be considered.
6. Sector neutrality: Tools should not be limited to a particular industry sector.
7. Relevant: The tool should be at the time of research available. Tools that are not currently available will be excluded, unless they are frequently cited in recent literature (from 2014 onwards).

From these criteria 23 tools will be selected for further analysis.

Preferred Tools

To evaluate which tools are preferred, various articles and case studies will be analyzed to determine where designers implement LCA-based tools in the design process. These case studies will be identified through the semi-systematic literature review on tools. This research will define what type of tools are preferred and whether there is an industry standard.

Tool Usability

From the tools analyzed in the previous section, four of the preferred LCA tools will be selected for further usability inspection in an illustrative case study. The tools will be selected through what is available and according to what is found to be a relevant industry standard in design processes. Demo requests will be sent to different tools, as well as educational tools will be searched. The educational and free tools that will be analyzed are Fast-Track LCA Teaching Tool and Footprint Calc. In addition, two tools will be selected which require a demo request.

The goal of the case study is to find out what aspects of a tool can improve the usability of the tool and make it more understandable for the user. Additionally, it is relevant to see what the capabilities and workflows are of the current state-of-the-art tools that are relevant for designers. Lastly, it is relevant to see what the strengths and limitations of each tool are in practical applications to provide a comprehensive understanding of their overall performance and reliability.

The four tools will be used to assess the same two product alternatives. The information of these alternatives is from a master's elective course. The workflow of the tools will be analyzed on four categories and subcategories (**Table 3**), which were adapted from (Chatty et al., 2021). The LCA modeling, and analysis will be performed by the researcher.

Table 3. *Usability categories and attention points.*

Category	Attention Points
Ease Of Use	Time needed to complete
	Ease of workflow
	Tool complexity
	Ability to model what is required
Data Quality	Room for uncertainty
	Database transparency
	Database availability
Conceptual Design Phase Fit	Level of detail
	Time needed to complete
	Actionable results
Results Comparison	Account for uncertainty in visualization

	Visualization of the results
	Impact assessment options
	Ability to compare

It should be noted that the analysis conducted by the researcher is subject to several limitations. Firstly, this may potentially influence the assessment of usability, as the researcher's familiarity and comfort with certain tools may affect the effectiveness with which they are used. To address this issue, the tools selected have not previously been used by the researcher. Moreover, as the researcher's engagement with the tools differs from that of typical end-users, the evaluation may not fully capture the challenges and experiences faced by designers in real-world settings. To address this limitation, the researcher has a background in product design and evaluated the findings with two design students. However, these limitations must be considered when interpreting the findings, as they may impact the applicability and reliability of the conclusions drawn regarding the tools' usability and effectiveness.

2.3.4. SUB-RESEARCH QUESTION 4

A combination of empirical data and existing research will be used to answer the fourth sub-RQ: *"What challenges do designers face in making early decisions about environmental sustainability in the design process, and how could this be improved?"* This approach includes interviews, a case study and a literature review to gain an understanding of the current landscape and potential improvements.

Exploring the Challenges of Tool Implementation

The empirical data will be gathered through semi-structured interviews with two companies (Company A and Company B) with extensive product portfolios in the consumer electronics sector.

The interviews will be conducted with experienced sustainability experts and product designers who are responsible for developing environmental and circularity assessment tools for their respective companies. Both companies are engaged in the development of in-house assessment tools for environmental and circularity evaluation.

The objective of the interviews is to gain insights into the methods and tools employed during the design phase and to identify the challenges encountered during implementation. To this end, the interviews will be conducted using a set of guiding questions designed to provide the required responses. The questions will include the following:

- What are the current challenges associated with existing environmental sustainability assessment tools?
- Please describe the rationale behind the decision to develop your own environmental sustainability assessment tool.
- What is the intended purpose and role of the tool within the design process?
- What challenges are currently being faced in the development of the tool?

In addition, case study information from Company C, a large retailer of low-cost consumer goods, will be provided via email, detailing their use of the tool.

Table 4. *Overview empirical data research.*

Research Type	Company	Description
Semi-structured interview	Company A	Developed their own circularity and fast-track LCA tools.
	Company B	Did not currently utilize any environmental sustainability assessment or circularity tools. Company is in development of an in-house benchmarking tool with a circularity toolset.
Case study	Company A	Utilizes an external circularity and environmental measurement tool: Circular Transition Indicator (CTI).

To complement the empirical data, existing literature will be reviewed to provide additional context and insights into the challenges of implementing environmental sustainability assessment methods. This review will utilize forward snowballing from key articles, such as *"Eco-design Maturity Model: A Management Framework to Support Eco-design Implementation in Manufacturing Companies"* by Pigosso et al. (2013) and *"Defining the Challenges for Eco-Design Implementation in Companies: Development and Consolidation of a Framework"* by Dekoninck et al. (2016). The literature review will continue until data saturation is achieved, resulting in a comprehensive overview of challenges supported by approximately 20 relevant articles.

Identifying Areas for Improvement

The challenges identified will be analyzed to determine potential improvements in current tools and methods. Factors influencing these challenges will be categorized as drivers and barriers. This analysis will reveal shortcomings in existing tools and identify areas where enhancements are needed to facilitate improved decision support.

The final stage will entail the definition of enablers, that is, elements that could be introduced or improved to provide more effective support to designers. This will include the development of criteria for the evaluation of potential solutions and improvements to tools. The objective is to make environmental sustainability assessments more accessible and integrated into designers' workflows, thereby providing practical recommendations for enhancing the effectiveness of environmental sustainability assessment tools in the early stages of product design.

2.3.5. SUB RESEARCH QUESTION 5

In this sub-chapter, the following research question will be answered: "How could an environmental sustainability assessment tool be designed and structured to facilitate designers in early-stage decision-making on the environmental impacts of circular design strategies?" The final Sub-RQ will be answered by combining the findings from the previous research approaches into a detailed program of requirements that will serve as the foundation for subsequent tool development.

Developing the Program of Requirements

The previous Sub-RQs will provide insights into possible improvements and opportunities for better facilitation of environmental sustainability assessment early in the design process. The following insights will be gained:

- Sub-RQ1: This will identify what the designer's decision-making process will entail during the early stages of the design process
- Sub-RQ2: This will identify methods capable of assessing both circularity and environmental impacts.
- Sub-RQ3: This will reveal the types of tools that designers prefer and the reasons behind their preferences.
- Sub-RQ5: This will highlight the challenges faced when using current tools and emphasize what aspects in tool development need changing for more suitable use during the early design process.

The program of requirements will be assembled using the method proposed in the Delft Design Guide by van Boeijen et al. (2013). This method provides a clear framework for creating a comprehensive and hierarchical list of objectives and goals for the tool, ensuring that it meets the needs identified through the research. A comprehensive list of potential requirements will be continuously updated and iterated throughout the analysis and summarization of the results of the research on sub-RQs. Additionally, expert feedback will provide further refinement of the requirements. These requirements will be categorized into the MoSCoW framework: must-haves, should-haves, could-haves, and won't-haves (Clegg & Bakrer, 1994). The won't-haves will be eliminated, and similar requirements will be grouped into categories. Furthermore, all requirements included in the program will be made testable. This will be achieved by determining variables that are observable or quantifiable characteristics. Finally, the requirements will be developed by following six conditions:

- Each requirement must be valid.
- The set of requirements must be as complete as possible.
- The set of requirements must be operational.
- The set of requirements must be non-redundant.
- The set of requirements must be concise.
- The set of requirements must be practicable.

The program of requirements will be further extended with the ISO guidelines (International Organization for Standardization [ISO] 14040, 2006; ISO 14044, 2006))of conducting an LCA and the additional existing and upcoming legislative requirements aimed to standardize environmental sustainability assessment on product level. Examples of these policies are the CSRD reporting framework and the ability to use the European Commission's PEF as impact assessment. The final list will serve as the foundational framework for the development of an environmental sustainability assessment tool.

An example of how these requirements can be integrated into the framework will be provided to illustrate the practical application of the developed tool. This example will demonstrate how the tool can be structured to meet the identified needs and challenges, thereby facilitating more effective environmental sustainability assessments in the design process.

3.

DESIGN THEORY AND PRACTICE

Given the focus of this research on the interrelations between design practice, particularly circular design, and environmental sustainability assessment, it is essential to establish a solid theoretical foundation. This first results chapter explores the foundational concepts and theories that inform design processes, with a particular focus on how designers navigate early-stage decision-making to integrate environmental sustainability.

The structure of the chapter is as follows: First, the theoretical and practical aspects of design are examined through an investigation of diverse design methods. Second, the workflow during the initial stages of a design process is analyzed in regard to the role of the designer within an interdisciplinary team. Finally, the chapter examines the cognitive processes of the designer during the early stages of a design project, discussing the relations between intuitive and analytical decision-making processes and the challenges of integrating environmental sustainability assessments into early-stage design workflows.

3.1. DESIGN THEORY

The evolution of design theory and practice has been significant since the early 20th century. Initially, it was perceived as an intuitive pursuit led by skilled artists with limited procedural knowledge (Neramballi, 2022; Roozenburg & Eekels, 1998; van Boeijen et al., 2013). Over time, the field of design has expanded beyond its traditional focus on form and function, embracing a diverse range of methods and tools that extend its scope beyond the functionalities of products (van Boeijen et al., 2013).

In recent decades, there has been a notable shift towards strategic and systemic design approaches, emphasizing the inclusion of services, business models, and ecosystems alongside traditional product design. This evolution has transformed design into an interdisciplinary field that integrates creativity with systematic methods to effectively tackle complex challenges (Baldassarre et al., 2020). This expanded role of designers extends beyond creating industrial products to co-creating sustainable business models with multiple stakeholders and envisioning long-term futures (Bocken et al., 2023; Diehl & Christiaans, 2015; Goss et al., 2024). Recognizing their potential to address complex challenges, designers are increasingly applying design thinking to advance the CE, reevaluating industrial processes and broader socio-technical systems (Bocken et al., 2023)

The term "designing" is open to a variety of interpretations and is used in this research to refer to the process of creating products, services, and systems (Ellen MacArthur Foundation, n.d.). It involves synthesizing diverse objectives in order to meet specific contextual needs and desires (Roozenburg & Eekels, 1998), utilizing creativity, intuition, expertise, and structured design methods in order to generate outcomes that address specific challenges or opportunities (van Boeijen et al., 2013).

3.1.1. THE DESIGN PROCESS

The design processes employed by practitioners are significantly diverse, reflecting individual experiences and project contexts, which complicates the establishment of a standardized procedure. Companies adapt their processes based on their purpose and context (Kim, 2016). Despite this variability, several methods share common stages, namely analysis of, conceptual design, embodiment design and detailed design (Gericke & Blessing, 2012). The start of a design process often comes from finding a problem or challenge that could be improved. This can be in an unexplored context, but most frequently an already existing product requires improvement. The Basic Design Cycle, proposed by Roozenburg & Eekels (1998), adopts a trial-and-error approach where problem understanding, and design knowledge evolve iteratively through distinct methodological steps. These stages include analysis, synthesis, simulation, evaluation, and decision-making. When a design proves unsatisfactory, designers revert to earlier synthesis and analysis stages for refinement (Roozenburg & Eekels, 1998).

Another popular approach, the Double Diamond approach, introduced by the Design Council (2005), offers a widely recognized and adaptable framework structured around four key steps: discover, define, develop, and deliver. Unlike the linear progression of the Basic Design Cycle, the Double Diamond incorporates elements of divergence and convergence, fostering iterative problem-solving through exploration, problem definition, solution development, and implementation (the Design Council, 2005). Despite variations in terminology and visual representation, both methods emphasize iterative refinement driven by feedback, allowing designers to tailor frameworks effectively to meet project requirements.

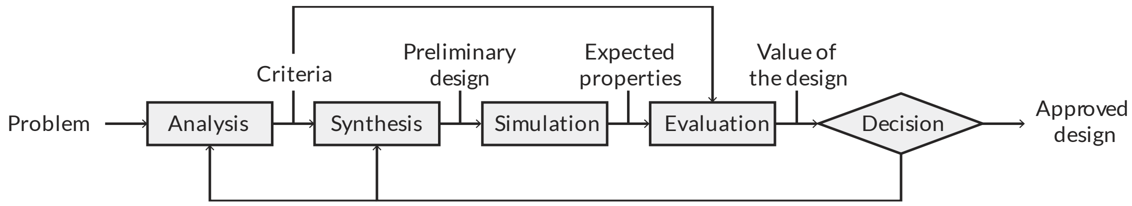


Figure 5. *Basic Design Cycle. Image from Roozenburg & Eekels (1998).*

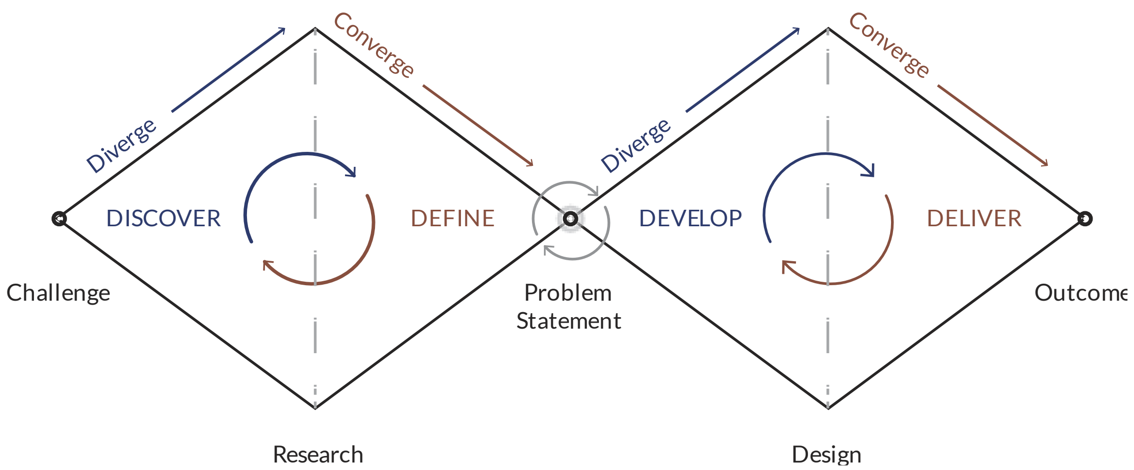


Figure 6*. The Double Diamond. Image adapted from the Design Council (2005).*

Structured guidance is a fundamental requirement throughout the design process, facilitating effective navigation of complex challenges and clear communication of findings. Design methods assist in the advancement of design research and provide partitioners with systematic guidelines.

Design methods employ a range of strategies, methods, and tools to stimulate creativity and aid designers in understanding the context of design problems. The utilization of these approaches varies widely, from simple aids like mind mapping to comprehensive methods that facilitate forward-thinking and innovative design, such as Vision in Product (van Boeijen et al., 2013). Each method serves the specific function of advancing the designer's progress within a project, the design methods are therefore flexible in their use, only used until the advancement is achieved (Daalhuizen, 2014). These methods often aim to reduce complexity and uncertainty, thereby assisting designers in achieving their desired outcomes efficiently and effectively (Matschewsky et al., 2024).

3.1.2. EARLY STAGE OF THE PRODUCT DESIGN PROCESS

The aimof this research is to facilitate an environmental sustainability assessment tool that seamlessly integrates into the early-stage design workflow. Therefore, it is important to define what is meant by the early design phase, and what kind of tasks are performed during this phase.

The Design Council (2005) categorizes the design process in four phases: discover, define, develop, and deliver. The two initial phases (discover and define) are often referred to as the "fuzzy front-end" since they typically involve ad hoc decisions, uncertainty and ill-defined processes. The objective of the fuzzy front-end is to articulate the central challenges and opportunities, achieved through continuous and unstructured experimentation and research which can often be chaotic, eventually providing an outline what can be designed (Almqvist, 2017).

Hay et al. (2017) categorizes designing into four main activities: problem structuring/analysis, generation and synthesis, evaluation, and decision-making. The conceptual design phase is situated within the first two phases. It marks the beginning of concept development and is placed between identifying an opportunity or challenge until a concept is chosen and development can be started (Kim & Wilemon, 2002). In the conceptual phase, characterized by a high degree of uncertainty and creativity, often relies on intuitive and creative processes. Additionally, this phase establishes the foundation for technical design solutions and should already consider significant design decisions (Boorsma, 2022). The tasks undertaken during the conceptual design phase include the identification and anticipation of market opportunities, the understanding of customer desires (Haber & Fargnoli, 2021) and the iterative transformation of a design brief into different solution concepts through ideating on ideas and testing prototypes.

Van Dooren et al. (2018) suggests the conceptual design phase consists of five generic elements. Frist, experimenting which consists of continuous testing and evaluating of hypothesis. Second, a guiding theme, something that gives the designer direction in the problem solution space, which is achieved by experimenting. Third, the different domains, which gives context to the design projects. Fourth, a frame of reference, providing the designer with knowledge which is built consciously and unconsciously. Lastly, the design language, making the ideas visual and explicit, while exploring new possibilities and discovering new insights. The designer moves through these elements while experimenting, causing a chaotic and iterative path, as seen in **Figure 7.**

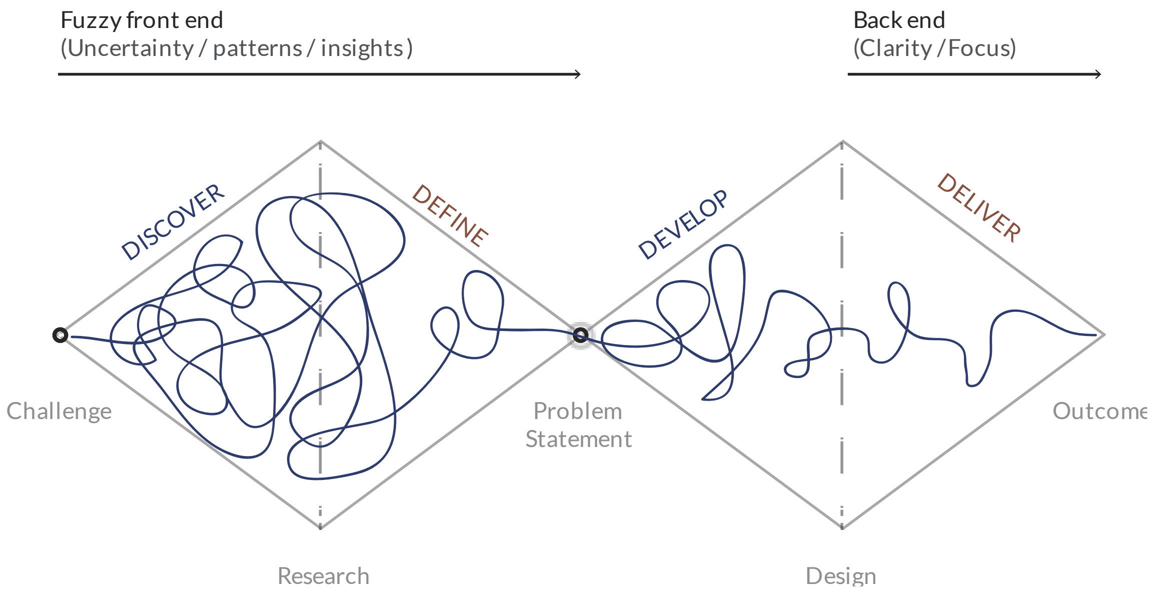


Figure 7*. The iterative design process during the conceptual design phase. Image combines the double diamond with the five generic elements in the design process (the Design Council, 2005; van Dooren et al., 2018).*

3.1.3. THE DESIGNER'S ROLE IN INTERDISCIPLINARY TEAMS

Designers play a central role in both business and society, consistently working within multidisciplinary teams that integrate diverse perspectives and expertise. Designers are increasingly adopting a 'spider-in-the-web' approach, integrating varied inputs and considering all perspectives (Baldassarre et al., 2020). This can also be seen in research on interdisciplinary design teams, where designers are viewed as essential for tackling complex challenges, envisioning novel futures, and driving innovation (Badke-Schaub & Gehrlicher, 2003; Välk et al., 2023). The composition of these interdisciplinary design teams varies by sector and organization, incorporating different areas of expertise as needed.

Collaboration and trust are focal points within design teams. Trust is established through the dissemination of knowledge, the establishment of mutual agreements, and the creation of a shared understanding. The dialogue that occurs during design negotiations serves to bridge the gap between expert and non-expert knowledge, thereby enhancing comprehension of the design context (Nguyen & Mougenot, 2022). Furthermore, team dynamics and organizational conditions have been identified as key factors influencing the effectiveness of the design process (Badke-Schaub & Gehrlicher, 2003). Particularity during the iterative conceptualization phase cycles, effective knowledge sharing, and communication are crucial, as the design team continuously refines both problem and solution spaces (Heck et al., 2020).

For the purposes of this thesis, a design team is defined as an interdisciplinary team consisting of a variety of expertise, with the designer being a fundamental component. When referring to the designer, this thesis specifically refers to the role and responsibilities of the designer within such a team.

Furthermore, designers are able to influence strategic decisions at multiple levels, including product lifecycles, service interactions, business models, and entire ecosystems. This strategic involvement has been shown to promote sustainable development by encouraging organizations to consider environmental and social impacts alongside economic goals (Baldassarre et al., 2020).

3.2. DESIGN THINKING

The design thinking process is characterized by its iterative nature, involving multiple stages that enable continuous refinement and adaptation of ideas (the Design Council, 2005). This dynamic approach allows designers to explore diverse solutions and adjust concepts based on feedback and functional requirements. This sub-chapter dives into the cognitive aspects of design thinking, how this relates to the designer's workflow and the connection with environmental sustainability assessment.

3.2.1. HOW DESIGNERS THINK: DUAL-SYSTEM THEORY

In the design process, designers blend intuition and reasoning, utilizing both imaginative thinking and structured methods to navigate complex problems. According to the dual-process theory, human cognition operates through two distinct systems: System 1 and System 2 (Kahneman, 2011). System 1 is characterized by fast, intuitive, and effortless thinking, often driven by emotions and gut feelings. In contrast, System 2 involves slow, analytical, and effortful thinking, which relies on logical reasoning and deliberate analysis (Kannengiesser & Gero, 2019).

Designers operate within these two cognitive systems, switching between them as needed throughout the design process. System 1, with its intuitive processing, allows creativity to flourish. Designers often rely on this system for quick insights drawn from expertise and the generation of novel ideas. Research indicates that design intuition is holistic, fast, multisensorial, and experience-based (Badke-Schaub & Gehrlicher, 2003). Empirical studies have shown that designers often jump to concrete concepts early in the design task, leveraging their intuition to swiftly generate solutions (Kannengiesser & Gero, 2019).

On the other hand, System 2 encompasses the more deliberate and structured aspects of the design process. This system comes into play when designers engage in detailed analysis, planning, critical evaluation, and logical reasoning to refine and validate their ideas. Furthermore, System 2 monitors and assesses the decisions made by System 1 (Kannengiesser & Gero, 2019).

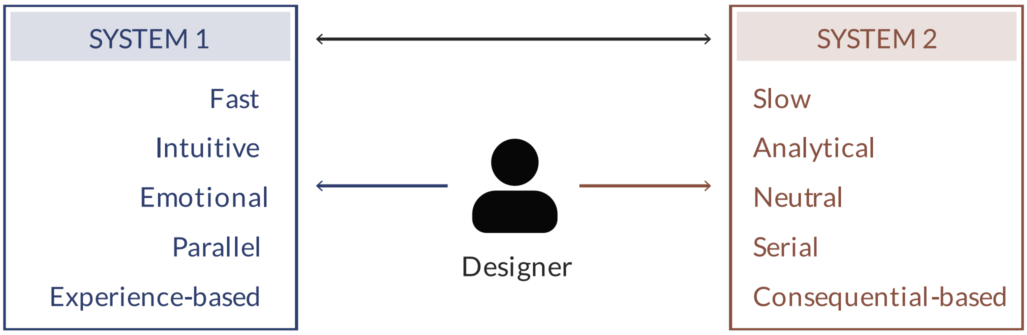


Figure 8. *Dual process theory (Kannengiesser & Gero, 2019; Neramballi, 2022).*

The research of Gonçalves & Cash (2021) made a connection between the dual system theory and the ideation and concept generation process. During these initial stages of the design process, System 1 thinking is the predominant method of judgment, with most ideas being evaluated rapidly using past experiences or gut feeling. System 2 thinking is employed in more deliberative decision-making at a later stage in the design process. As soon as a designer encounters a design problem, System 1 begins to develop the initial ideas. When given priority to developing ideas through System 2, concepts that were previously intuitively judged in System 1 still tend to be accepted.

In this thesis, the early stage in the design process is defined as the period following the fuzzy front end, when the opportunity is defined, up until the end of the conceptual phase. Throughout this phase the designer makes intuitive and fast paced decisions, guided by creativity. In this phase, System 1 thinking is primarily present. An environmental sustainability assessment conducted at this stage in the design process can serve as a foundation for the final decisions made during the embodiment phase regarding materials, functionality, aesthetics, and business models.

3.2.2. INTEGRATING ENVIRONMENTAL SUSTAINABILITY ASSESSMENT WITH THE DUAL PROCESS THEORY

Designers' reliance on intuition and rapid ideation during the early stages of the design process could clash with the structured, analytical nature of environmental sustainability assessment tools like LCA. Dual-system theory explains that designers switch between intuitive (System 1) and analytical (System 2) thinking; however, the early design stages are predominantly governed by intuitive thinking (System 1). This phase prioritizes creativity and the quick generation of ideas based on experience and gut feelings (Gonçalves & Cash, 2021; Kannengiesser & Gero, 2019). In contrast, conducting an LCA requires analytical thinking (System 2), which is systematic, deliberate, and data-driven.

Designers work within broad and undefined contexts, where problems are understood, and ideas are generated through iterative testing and defining (the Design Council, 2005). This design process involves multiple stages, including ideation, prototyping, and development, allowing for continuous experimentation leading to adaptation and improvement based on user feedback and functional requirements (Daalhuizen, 2014; van Dooren et al., 2018). The iterative and innovative nature of the early stages in the design process enables designers to explore a wide range of solutions, refine concepts, and adjust ideas based on testing and evaluation. However, the LCA framework, while also iterative, follows a more structured and analytical approach compared to the creative and flexible design process. LCA requires iterative adjustments aiming to improve accuracy and completeness, particularly during the interpretation phase, where findings may prompt revisiting previous steps to refine data and analysis (Sander-Titgemeyer et al., 2023).

The potential clash between these two cognitive processes—intuitive ideation and analytical assessment—presents a significant challenge in integrating LCA into the early design stages. While System 1 thinking enables designers to explore a wide range of creative solutions rapidly, the transition to System 2 thinking for LCA can disrupt the flow of ideation, potentially leading to design fixation and a reduction in creative capacity (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2016). However, when looking into the elements of a design process (van Dooren et al., 2018), LCA has the potential to facilitate as an experimenting tool, testing different theories and providing the designer with direction. This underscores the necessity to develop version of LCA tools that integrate seamlessly with the early-stage design workflow.

4.

THE LANDSCAPE OF ENVIRONMENTAL SUSTAINABILITY ASSESSMENT

The research design outlined in the previous chapter provided an overview of the approaches used to address the Sub-RQs. This chapter presents the results of the analysis conducted during the research. It is structured as follows: First, the chapter discusses the environmental sustainability assessment methods and evaluates their effectiveness in assessing circularity. Next, it examines the currently available tools and how they are used. Lastly, it addresses the challenges that designers face when implementing circular and eco-design principles.

4.1. ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF CIRCULAR DESIGN STRATEGIES

This subchapter follows the approach outlined in **section 2.3.2.** The section is structured by first identifying the circular design strategies, followed by defining the frequently mentioned methods and other relevant methods through a semi-systematic literature review, resulting in an overview of 20 eco-desogn methods that can be used in the design process. These were tested for their ability to assess the environmental impacts of the five different circular design strategies.

4.1.1. SELECTION OF CIRCULAR DESIGN STRATEGIES

Circular design strategies aim to improve environmental sustainability throughout a product's lifecycle, but there is a lack of consensus on definitions and categorizations (den Hollander et al., 2017; Ellen MacArthur Foundation & IDEO, 2017; Haffmans et al., 2018; Moreno et al., 2016; Potting et al., 2017; Reike et al., 2018). Frameworks like the R-framework (Potting et al., 2017) and the Circular Economy Systems Diagram (Ellen MacArthur Foundation, 2019) are commonly used, emphasizing maintaining resource value and separating biological and technical cycles. Other research categorizes strategies into narrowing the loop, slowing down the loop, closing the loop, and regenerating (Bakker et al., 2014; Bocken et al., 2016; Konietzko et al., 2020)

Since the rise of circular design, a new configuration of strategies has been developed that integrates Design for X (DfX) approaches with systems thinking to transform the role of design within the Circular Economy (CE) (den Hollander et al., 2017; Moreno et al., 2016). This perspective is essential for contemporary design practices focusing on environmental sustainability and circularity. Notably, five strategies incorporate this systems perspective: (1) Design for Circular Supplies emphasizes biological cycles and the 'waste equals food' principle, aiming to minimize environmental impacts with reused and recycled content; (2) Design for Resource Conservation reduces material consumption and hazardous substances; (3) Design for Multiple Cycles enables longer resource cycles through easy disassembly and refurbishment; (4) Design for Long-Life Use extends product use with durable designs and sharing options to delay disposal; and (5) Design for Systems Change considers complex interactions and innovative business models to enhance multifunctionality.

This thesis proposes circular design strategies tailored to environmental sustainability assessment, thereby providing clear differentiation and focus on specific environmental impacts and benefits. The structure is adapted from (Moreno et al., 2016) however, further defined as specified. These strategies are:

- Design for Circular Regeneration emphasizes the use of the 'waste equals food' principle to minimize environmental impacts. This strategy promotes reused and recycled content, focusing on renewable sources, and closed-loop systems.
- Design for Resource Efficiency focuses on minimizing resource use by reducing material consumption and promoting recycling practices. This strategy aims to lower the environmental footprint by using fewer or fewer materials in the manufacturing and use phase while maximizing recovery at the EOL.
- Design for Multiple Cycles facilitates longer resource cycles by designing products for easy disassembly and refurbishment. This approach includes refurbishing, remanufacturing, repurposing, and recycling to maximize material utility.

- Design for Long-Life Use of Products extends product lifespan by promoting emotionally and technologically durable designs. This strategy emphasizes repair and maintenance, increasing product durability and user satisfaction to delay disposal.
- Design for Rethinking Systems encourages the development of innovative business models that prioritize circularity. This strategy involves the design of multifunctional products and the avoidance of unnecessary consumption.

Further details on the existing circular design strategies and how they relate to the proposed strategies can be found in **APPENDIX B.** Corresponding to these strategies, are the selected indicators to define these strategies. These indicators are derived from definitions and indicators of the different circular strategies presented above.

Table 5. *Circular design strategies and representative indicators.*

Circular Design Strategy	Indicators
Design For Circular Regeneration	Use of recycled content
	Use of reused components
	Amount of virgin material in use
	Critical material use
Design For Resource Efficiency	Material efficiency
	Water consumption
	Energy consumption during life cycle
Design For Multiple Cycles	Reusability
	Design for remanufacturing
	Design for recycling
Design For Long-Life Use Of Products	Durability
	Product architecture
	Repairability
	Upgradability
Design For Rethinking Systems	Circular business models
	Outcome mapping
	Multifunctionality

4.1.2. ECO-DESIGN APPROACHES AND ENVIRONMENTAL SUSTAINABILITY ASSESSMENT.

A semi-systematic literature review was conducted to which eco-design approaches that use environmental sustainability assessment methods can assess the environmental implications of circular design strategies. The complete overview of relevant eco-methods with integrated environmental sustainability assessment is presented in **Appendix A**. This section proposes the 20 selected methods from the overview. According to the eco-design framework (ISO 14006, 2020), the environmental sustainability assessment methods selected can qualitatively or quantitatively assess products in terms of their environmental impact and guide environmentally beneficial improvements throughout their lifecycle.

Methods from Design Practice and Management

A review of the literature revealed that researchers frequently combine established design methods with environmental sustainability assessment approaches to develop eco-design methods that are specific to decision support. The main methods identified from design practice include Quality Function Deployment (QFD) and the Theory of Inventive Problem Solving (TRIZ).

QFD is a method used to understand and prioritize customer requirements while establishing technical and functional design priorities (Otto & Wood, 2001). The QFD method is a four-phase matrix that provides a conceptual map for the design process. In the context of eco-design, QFD includes environmental requirements alongside customer requirements and integrates these additional criteria into the design process. This integration ensures that both customer needs and environmental impacts are addressed in engineering characteristics, creating a balanced approach to environmentally sustainable design. It is important to note that inputs to QFD-based eco-design methods rely heavily on expert knowledge and intuition, which can introduce subjectivity into the process and little consideration of the life cycle (Brundage et al., 2018; Ramani et al., 2010).

TRIZ is a framework that seeks to forecast novel technologies and products while discovering inventive and creative solutions to complex problems (Feniser et al., 2017). In the last two decades, TRIZ tools have been widely used in the primary stages of eco-design to facilitate eco-innovation and technical problem solving (Boavida et al., 2020). The TRIZ method is inherently integrated with environmental sustainability principles, employing qualitative and quantitative approaches such as 'dematerialization' and 'reduce waste'. This enables companies to identify potential innovations that contribute to environmental sustainability (Feniser et al., 2017; Spreafico, 2022).

Environmental Sustainability Assessment Methods in Eco-Design

In addition to design methods, environmental sustainability assessment in eco-design is supported by adapted qualitative, semi-quantitative or quantitative assessment methods. These methods often include a full-scale LCA or a simplified approach, derived from LCA, such as screening, fast track, or streamlined LCA. An example of a streamlined semi-quantitative approach is the Environmentally Responsible Product/Process Assessment (ERPA) Matrix (Graedel, 1998). A semi-quantitative method incorporates both qualitative and quantitative approaches. This may be achieved, for example, by capturing both the measurable impacts and the subjective evaluations. The assessment consists of a 5x5 matrix, with one dimension being the life cycle stages and the other the environmental concerns. Each cell is assigned a rating from 0 (highest impact) to 4 (lowest impact), based on a checklist. To streamline the process, different aspects of an LCA are neglected. For ERPA, for instance, the method excludes electricity production (Hochschorner & Finnveden, 2003). These kinds of approaches are used to quickly indicate which processes can be improved. Other environmental sustainability assessment methods are not linked to LCA but do include a life cycle thinking (LCT) approach. For instance, the eco-design strategy wheel (Brezet & van Hemel, 1997). This method links different strategies to phases of the product's lifecycle. Designers can then qualitatively assess how their products perform according to these strategies in a spider diagram.

Table 6*. Selected eco-design methods (Qn = Quantitative, S-Qn = Semi-Quantitative, Ql=Qualitative).*

Group	Method	Brief Description	Linked Methods	Research Type	Reference
Analytical	Full-scale LCA	Method to evaluate environmental burdens associated with a product's lifecycle.	LCA	Qn	ISO 14040 (2006)
	Life Cycle Planning (LCP)	Integrates long-term planning, quality, cost, and environmental aspects into the early lifecycle.	LCA QFD TRIZ	S-Qn	Kobayashi (2005)
	Product Carbon Footprint (PCF)	Accounts for overall GHG emissions of a product, including both carbon and biogenic sources.	LCA	Qn	ISO 14067, (2013) British Standards Institution [BSI] (2011) Sanyé-Mengual et al. (2014)
	Adapted QFD: QFD for the Environment QFDforPSS	QFD is adapted to fulfil different requirements of the researcher.	LCA QFD TRIZ	S-Qn	QFD-E: Sakao (2007) QFDforPSS: Haber &

	Lifecycle function deployment (LFD) QFD - CE	All follow similar patterns, obtaining stakeholder insights while simultaneously developing specific environmental criteria.			Fargnoli (2021) LFP: Neramballi (2022) QFD-CE: Siwiec et al. (2023)
	STARDUST method (Strategic layered double-flow scenario modeling for sustainability risk and portfolio management)	The method is developed to guide companies in integrating a strategic sustainability perspective into the product portfolio process. It was designed to provide practical support for how a portfolio can be assessed considering sustainability (Sustainability LCA), market success, and changes over time (Back casting method).	LCA	S-Qn	Villamil et al. (2022)
Comparative	Streamlined / screening LCA	Simplified LCA models that maintain technical features while making the method more feasible.	LCA	Qn/s-qn/ql	Bennett & Graedel (2000)
	Qualitative Matrix: MET (Material Energy, and Toxicity) Matrix ERPA (Environmentally Responsible Product/Process) Assessment Matrix DFE Matrix (Design for the Environment)	Matrices that summarize environmental impacts per life cycle stage using qualitative assessments. MET: Two matrices, first, impacts of materials, energy, and toxicity against the product's life cycle. The second matrix qualitatively estimates the severity of the cases. ERP: In each cell, the studied system is on a scale, 0 to 4, based on its perceived performance. DFE: environmental concerns are expressed in various questions. Each cell is rated 0-5 based on the	LCT / LCA	Ql	MET: Brezet & van Hemel (1997) ERPA: Graedel (1998) DFE: Yarwood & Eagan (2001)

		implementation of the questions.			
	Quantitative Matrixes: Material Energy Chemical Other (MECO) Matrix	Matrix calculating simplified environmental performance across lifecycle stages.	LCA	Qn	Wenzel et al. (1997)
	Eco-design Strategy Wheel / Lifecycle Design strategies (LiDs)	Scoring system for seven strategies to minimize environmental impact.	LCT	Ql	Brezet & van Hemel (1997)
	The Environmental Performance Strategy Map (EPSM)	Graphical representation integrating five footprints with a cost dimension to provide a single indicator.	LCA	Qn	De Benedetto & Klemeš (2009)
	BECE framework (Backcasting and eco-design for the circular economy)	Framework integrating back casting, LCA, and eco-design tools for circular business models.	LCA	S-Qn	Mendoza, Sharmina, Gallego-Schmid, et al. (2017)
Prescriptive	Eco-design checklist	Qualitative checklist for identifying environmental bottlenecks, often used with the LiDs wheel.	LCT	S-qn	Brezet & van Hemel (1997)
	Ten Golden Rules	Summary of guidelines for minimizing environmental impacts in product development.	LCT	Ql	Luttropp & Lagerstedt (2006)
	Checklist Sustainable Product Development (CSDP)	Qualitative checklist with 49 questions to encourage whole lifecycle thinking in design.	LCT	Ql	Schöggl et al. (2017)

4.1.3. ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF CIRCULAR DESIGN STRATEGIES

In **Table 7** the selected methods were assessed against the framework of five circular design strategies: Design for Circular Regeneration, Design for Resource Efficiency, Design for Multiple Cycles, Design for Long-Life Use of Products, and Design for Rethinking Systems. Representative indicators of each strategy were identified, see **APPENDIX B**, encompassing considerations such as material efficiency, reusability, durability, and the integration of circular business models.

Life Cycle Assessment and Circular Design Strategies

As illustrated in **Table 7**, LCA serves as the foundational method for the selected eco-design approaches, offering a structured framework for quantifying environmental impacts. LCA plays a pivotal role in modeling the initial three circular design strategies, namely, design for circular regeneration, design for resource efficiency, and design for multiple cycles. However, the modeling of the latter strategy presents a challenge due to the divergence of opinions within the field of environmental sustainability assessment (Schaubroeck et al., 2021).

One current issue in LCA is the allocation of environmental impacts across recycling or reuse loops, as LCA traditionally assesses impact on a per-product basis. A variety of allocation approaches exist, ranging from relatively simple to more complex. For example, the cut-off approach allocates the impact entirely to the initial use, whereas another approach divides the impacts equally between the initial and subsequent use cycles (Schrijvers et al., 2016). The distinct allocation approaches may be beneficial for different types of cycles, such as downcycling or equal-value cycling (van Stijn et al., 2021). The way impacts are allocated directly affects the results of environmental impact assessments conducted for each use phase (Malabi Eberhardt et al., 2020) The cascading of environmental impacts over multiple use cycles provides an incentive for stakeholders to engage in circularity within the system. Additionally, modeling reuse as well as other cascading strategies requires additional input for the replacement of products and the inclusion of inevitable outflow, which are often lacking in data and are specific to the product (van Stijn et al., 2021). Consequently, it is necessary to evaluate these options and make the choice explicit to accurately model the strategy of Design for Multiple Cycles.

Furthermore, LCA is not an optimal method for evaluating the circular design strategy of design for long-life use of products. While LCA can address different product lifespans, modeling aspects such as repair can be challenging. Baxter et al. (2024) argue that existing LCA studies lack clarity regarding the benefits of repair. Furthermore, while products may be designed to facilitate repair, the environmental benefits of this approach are not always readily apparent. Design for Long-Life Use of Products and Design for Rethinking Systems rely to a significant extent on non-quantifiable elements, including consumer behavior, ease of disassembly, and stakeholder involvement. These elements are challenging to quantify, which makes it difficult to include in LCA. While LCA's comprehensive nature makes it suitable for assessing the environmental performance of most circular design strategies, certain aspects, such as product durability, ease of disassembly, and modularity, may not be fully captured through traditional LCA metrics. To address these gaps, LCA is often integrated with other qualitative and semi-quantitative methods to provide a more holistic evaluation.

Eco-Design Methods and Environmental Implications of Circular Design Strategies

Table 7 outlines the performance of various eco-design methods in assessing the following circular design strategies: (1) Design for Circular Regeneration, (2) Design for Resource Efficiency, (3) Design for Multiple Cycles, (4) Design for Long-Life Use of Products, and (5) Design for Rethinking Systems.

Table 7. *Circular design strategies and related eco-design methods. (X : able to assess, / : partly able to assess, - : not possible).*

Nr	Methods	Circular Design Strategies					Outcome
		1	2	3	4	5	
1	LCA	X	X	X	/	/	Detailed analysis of different environmental indicators
2	PCF	/	/	/	/	/	Single indicator: GHG emissions
3	LCP	X	X	X	X	X	Lifecycle plan with relevant strategies to optimize value
4	QFD	X	X	/	/	/	List of environmental requirements
5	E-FMEA	X	X	/	/	-	Detailed analysis of environmental risks on all lifecycles
6	Simplified LCA	X	X	/	/	-	Hotspot indicators
7	EPSM	X	X	/	/	/	Spider diagram plotted the assessed footprints in percentage
8	STARDUST	X	X	X	X	X	Validated and environmentally evaluated CE scenarios and action plans
9	Qualitative Matrix	X	X	X	/	-	Summary of environmental impacts on all life cycles
10	Quantitative Matrix	X	X	/	/	-	Summary and severity of environmental impacts on all life cycles
11	BECE framework	X	X	X	X	X	Validated and environmentally evaluated CE scenarios and action plans
12	LiDs wheel	X	X	X	X	/	Possible strategies and qualitatively assessed fulfilment of strategies
13	Ten Golden Rules	/	X	X	X	-	Possible strategies
14	Eco-design Checklist	X	X	X	X	-	Possible strategies
15	CSDP	X	X	X	-	/	Possible strategies

Table 7 indicates that three integrated assessment methods can comprehend the different environmental aspects of circular design strategies. These methods are Lifecycle Planning (LCP), Strategic Layered Double-Flow Scenario Modeling for Sustainability Risk and Portfolio Management (STARDUST), and Back casting and Eco-design for the Circular Economy (BECE framework). These methods are reviewed in detail to find elements that could improve the comprehension of circularity within an environmental sustainability assessment tool. The reasoning behind the outcomes can be found in detail in **APPENDIX C.**

The LCP method demonstrates significant strengths in optimizing product value throughout the lifecycle. It emphasizes resource efficiency, multiple use cycles, long product life, and systemic thinking. LCP systematically plans and anticipates the use of circular content through a strategic planning approach in combination with LCA and an environmental requirements matrix, focusing on product longevity. It addresses long-term objectives, including product lifetime extension, setting target values, and assessing resource efficiency in the design phase. Additionally, LCP includes qualitative analyses for reusability, upgradability, maintainability, and recyclability, supporting multiple cycles and long product life (Kobayashi, 2005).

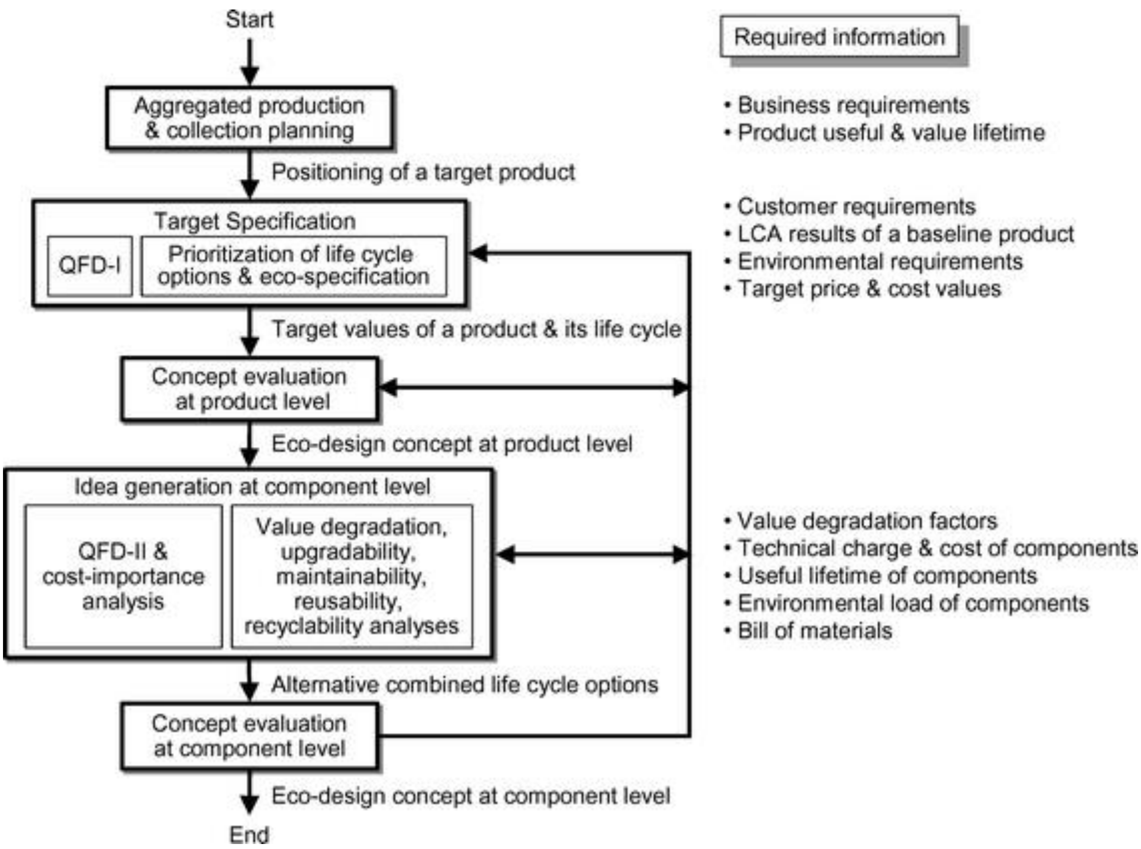


Figure 9. Steps of the LCP method (Kobayashi, 2005)

The STARDUST method covers all circular design strategies, ensuring comprehensive planning for CE implementation. It integrates circular regeneration principles into the product portfolio by assessing sustainability performance across lifecycles and timeframes. STARDUST evaluates resource efficiency through sustainability LCA and sustainability indicators, considering future resource constraints and technological innovations. It incorporates a holistic socio-ecological perspective, identifying opportunities for multiple cycles through remanufacturing, repair, and reuse, and supports decision-making for long-life products (Villamil et al., 2022, 2023).

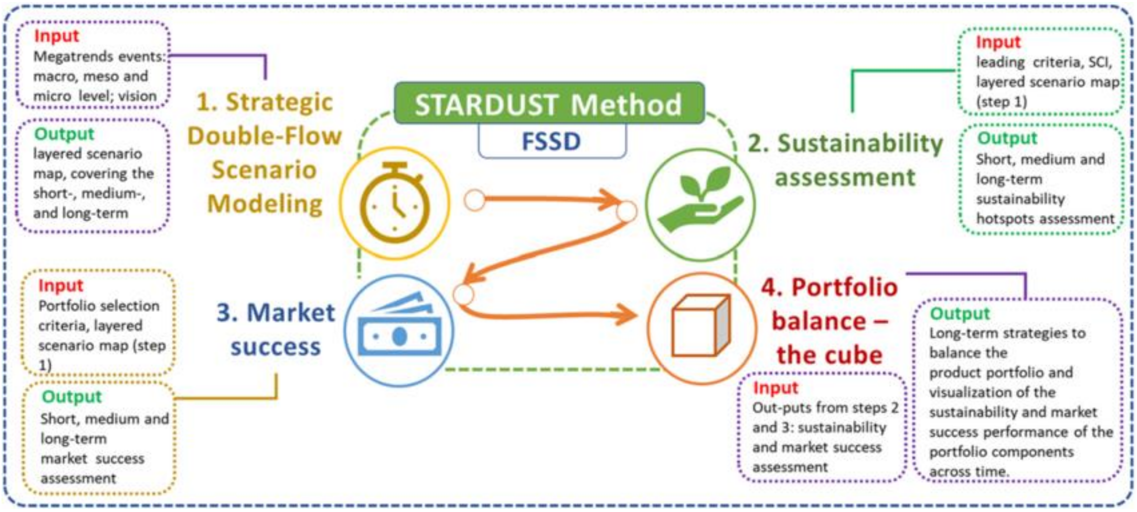


***Figure 10**. Steps of the STARDUST Method (Villamil et al., 2022)*

The BECE framework provides validated and environmentally assessed CE scenarios and action plans. It addresses all five circular design strategies and promotes a holistic approach to sustainability. BECE focuses on optimizing material and energy usage, incorporating recycled content and renewable sources. It uses LCA to identify resource consumption reduction avenues, along with qualitative product teardown to evaluate product architecture and ease of disassembly. BECE also incorporates back casting, fostering vision development, innovative business models, and system-level changes (Mendoza et al., 2017).

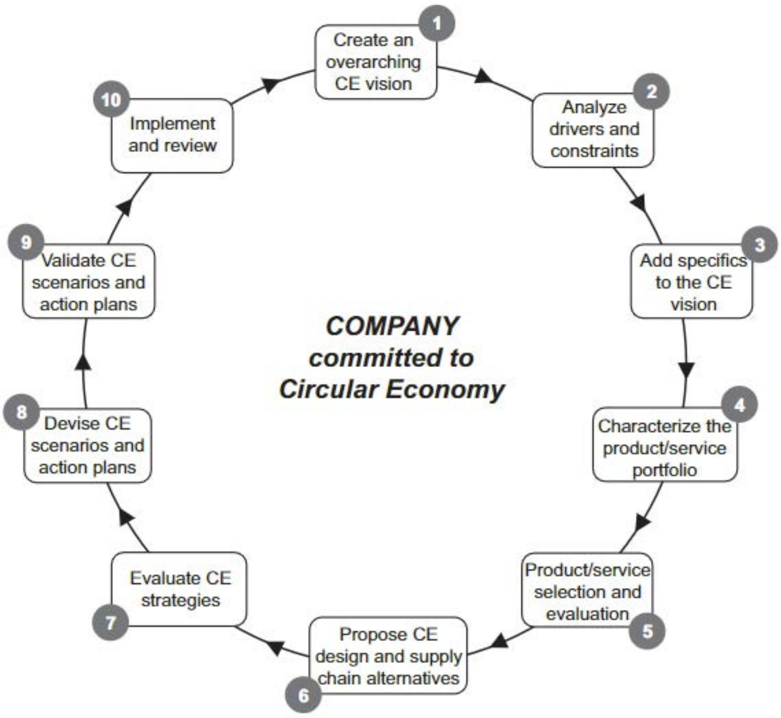


Figure 11. *Steps of the BECE framework (Mendoza et al., 2017)*

These three integrated assessment methods find common ground in their approach to incorporate LCA with qualitative assessment while providing a long-term perspective. The qualitative assessments within the tool allow for the evaluation of aspects within a product that have yet to be or cannot be quantified, most importantly, the product architecture, consumer behavior and ease of disassembly and repair. Allowing for qualitative input besides quantitative LCA results, the methods provide a holistic perspective for the environmental implications of the circular deign strategies. Furthermore, by incorporating a long-term perspective, they ensure that products designed are able with future adaptability and resilience, supporting ongoing system changes. Through facilitating ways designers and companies can strategically plan their circular design, they are able to anticipate future developments and requirements in their current designs. Making the designs more fit for a longer life span. It should be acknowledged that none of these methods are focused solely on the early-stage assessment of products. In addition, all three methods are time-intensive and require the involvement of stakeholders and other forms of complex features, hindering the intuitive and fast workflow during the early stages of a design process.

4.2. ENVIRONMENTAL SUSTAINABILITY ASSESSMENT TOOLS USED IN DESIGN PRACTICES.

This section addresses Sub-RQ2, exploring the use of LCA-based tools in design practices. An inventory of all relevant tools identified during the semi-systematic literature review, desk research, grey literature, and educational tools is provided in **Appendix A**. Based on this list, a selection of tools is presented in this section, along with a discussion of their usability in design practices.

4.2.1. OVERVIEW OF ENVIRONMENTAL SUSTAINABILITY ASSESSMENT TOOLS

Environmental sustainability assessment tools utilized in practice, based on LCA, can be classified into three main categories: software tools for full-scale LCA, software or web-based tools for simplified LCA, and plug-in tools for Computer-Aided Design (CAD) software. LCA software tools can conduct comprehensive LCAs and are frequently employed for detailed environmental impact assessment. Software or web-based tools for simplified LCA provide streamlined versions of LCA, offering quicker assessments that are suitable for conceptual design evaluations. Plug-in tools for CAD software integrate with CAD platforms to evaluate the environmental impact of specific product features, such as material production and weight. Other environmental sustainability assessment tools, such as tools that provide information and guidelines, were excluded from this research as it focuses on LCA-based tools.

Table 8 presents an overview of relevant tools found through the selection process described in **section 2.3.3**. The interfaces of these tools, showing their input panels as well as their output visualizations, can be found in **APPENDIX D.**

Table 8. *Overview of LCA-based Tools.*

Type Of Tool	Tool	Format	Output	Source
LCA	Activity browser	Software	Tables + Graphs	Steubing et al. (2020) GitHub (2024)
	Greenly	Software	Tables + Graphs	Greenly (2024)
	LCA for experts (Previously known as GaBi)	Software	Tables + Graphs	Sphera (2024)
	Mobius	Software	Tables + Graphs	Ecochain (2024)
	Makersite	Software	Tables + Graphs	Makersite (2024)

	OneClick LCA	Software	3D view + Tables + Graphs	OneClick LCA (2024b)
	OpenLCA Nexus	Software	Tables + Graphs	GreenDelta (2024)
	Simapro	Software	Tables + Graphs	Pré Sustainability (2024)
	Umberto	Software	Tables + Graphs	iPoint Systems (2024)
Simplified LCA	Cority (previously known as Enviance)	Software	Graphs	Cority (2024)
	EarthSmart	Software	Reports + Graphs + Tables	EarthShift Global (2024)
	Ecolizer Eco-design Tool (Discontinued)	Software / Website	Data resource + Graphs	OVAM (2023)
	Ecosketch	Software	Tables + Graphs	Chatty et al. (2024)
	EIME	Software	Tables + Graphs	Bureau Viritas (2024)
	EuPeco-profiler (Discontinued)	Software	Tables + Graphs	LiMaS Eco-innovation (2024)
	Fast-Track LCA Teaching Tool	Excel	Graphs	de Groot (2023)
	Footprint Calc	Excel	Tables + Graphs	The Footprinters (2024)
	Eco-Audit tool	Software	Report + Graphs	Ashby et al. (2021) Ansys Granta (2024)
	IDC LCA Calculator	Software / Website	Tables + Graphs	Industrial Design Consultants (2024)
	IdematLightLCA app	Excel	Tables + Graphs	Muersing & Vogtländer (2024)
	Sustainable Minds	Software / website	Report + Graphs	Sustainable Minds (2024)
CAD (Includes Simplified LCA)	Eco-design engineer (plug in 3d experience)	Software	Report + graphs	Dassault Systemes (2024a)
	Sustainability Xpress (plug in Solidworks)	Software	Report + Graphs	Dassault Systemes (2024b)

LCA tools

The most frequently mentioned LCA tools include SimaPro and GaBi (recently rebranded as LCA for Experts) (Birch et al., 2012; Brundage et al., 2018; Chatty et al., 2021; Delogu et al., 2018; Peace et al., 2018; Rossi et al., 2016; Rousseaux et al., 2017). In recent years, open access tools such as OpenLCA and Activity Browser in Brightway2 have also gained prominence (Delpierre et al., 2021; Martin et al., 2021; Palomero et al., 2024; Saidani et al., 2017). These tools require expert usage due to their diverse interfaces, databases, and approaches, increasing their complexity and allowing for specific modeling possibilities.

At a surface level, the utilization of these tools appears to be relatively similar, as all follow the ISO framework for LCA. However, the performance of these tools and their modeling methods differs significantly. **APPENDIX D** illustrates notable differences that can be seen in the LCA tool interfaces. Moreover, the research of Herrmann & Moltesen (2015) indicates significant discrepancies in data and calculation methods between LCA for Experts and SimaPro, employed to compute LCA outcomes. They demonstrate that both software tools exhibit deviations/errors at distinct stages in the calculations, ultimately resulting in notable discrepancies between the compared alternatives. While these differences do not have a direct effect on practitioners only using one software, they could cause problems when compared to the environmental impact of different benchmarks.

Simplified Life Cycle Assessment tools

Simplified LCA tools are increasingly being employed within the design process. These tools are frequently designed for use within the context of product design. Furthermore, simplified LCA tools are regularly developed for specific sectors. However, Sustainable Minds and Ecolizer are examples of simplified LCA tools that are commonly utilized across different industries by various companies (Brundage et al., 2018; Chatty et al., 2021; Rousseaux et al., 2017). Additionally, EIME (Environmental Improvement Made Easy) is also recognized in the literature as a commonly utilized tool. The tool is described as intuitive and designed to facilitate compliance with international standards (Rossi et al., 2016).

The primary distinction between simplified LCA tools and full-scale LCA tools is their reduction in complexity through the simplifying of steps that require additional knowledge or modeling time. Simplification strategies could include; using proxies in process data, using qualitative data, and establishing a threshold value to exclude less relevant components (Chatty et al., 2021; Hung et al., 2020; Samani, 2023). This results in restricted LCA modeling options, for instance, the is no flexibility when modeling the system boundaries, the open and closed loop recycling, the cut-offs, and the multifunctionality in simplified LCA tools. Eliminating these steps from the LCA has a significant effect on the accuracy and transparency of the results. However, these simplification efforts often decrease the modeling time of the tool significantly, making it better fit the beginning of a design process.

A recurring issue observed in the simplified LCA tools analyzed is their outdated datasets. This is due to the expensive licensing required for databases such as ecoinvent (2024), which results in the data used in simplified LCA models being frequently over ten to twenty years old. For example, data in Sustainable Minds ranged from the late 1990s up until 2020, with most data from the 2010s (Sustainable Minds, 2024) . The free Idemat dataset is often used in the context of license-free tools like the Footprint Calc and the Fast-Track LCA Teaching Tool. The Idemat dataset is consistently updated, yet it often still relies on outdated sources (Sustainability Impact Metrics, 2024). Other simplified LCA tools do utilize ecoinvent as their primary data source, with significant effect on the prices of the tools; examples include EcoSketch, EIME, and Ecolizer (Bureau Viritas, 2024; Chatty et al., 2024; OVAM, 2023). The IDC LCA Calculator also incorporates the ecoinvent database, although it utilizes version 2.2, which was last updated in 2010 (Industrial Design Consultants, 2024). The divergence in databases and their updates can have a considerable impact on LCA outcomes. The research of Miranda Xicotencatl et al. (2023) demonstrated that modifying the dataset from ecoinvent v2.2 to ecoinvent v3.6 resulted in differences ranging from -34% to 283%. This led to variations in the absolute amounts of the characterized results and the comparison between alternatives.

A significant outcome of the comprehensive desk research is that many simplified LCA tools have become inaccessible. Several tools mentioned in literature over the past decade, such as the preferred Ecolizer, have not been sustained as working software in the long term. Despite its popularity, it did not overcome its license issues with ecoinvent (OVAM, 2023). This highlights the challenges in developing and maintaining effective tools, which indicates an unstable landscape of LCA-based tools.

Computer-Aided Design environmental sustainability assessment tools

The Computer-Aided Design (CAD) tools of Dassault Systems, Sustainability Xpress, and Eco-Design Engineer provide an environmental impact report based on the 3D-modeled product (Dassault Systemes, 2024a, 2024b). It is important to note that these tools can model the LCA from cradle-to-gate through the product's BOM. The CAD tools do not include parametric design attributes (Brundage et al., 2018).

Using CAD modeling software for environmental sustainability assessments is appealing to designers, as it aligns with their working methods and accelerates the process (Beemsterboer et al., 2020). However, it is predominantly employed in the final stages of concept development, as the complete concept must be modeled with minimal uncertainty. Furthermore, the modeling of the LCA is constrained, like simplified LCA tools, which results in issues of accuracy and a narrow scope of results (Rossi et al., 2016).

4.2.2. DESIGNER PREFERENCES FOR TOOLS

Chatty et al. (2021) compared the usability of SimaPro and LCA for Experts to simplified LCA tools Earthsmart, Sustainable Minds, and Ecolizer to determine which ones are preferred by designers. The tools were evaluated on six criteria: learnability, ease of use, breadth and depth of database, reliability of results, effectiveness of results visualization, and costs. The study revealed that Earthsmart was perceived as the least capable due to its complexity and ineffective visualization results. In contrast, Sustainable Minds and Ecolizer were favored for their ease of use, low costs, and learnability.

The research of Pollini & Rognoli (2021) also refers to simplified LCA tools as to better align with the usability needs of the designers. They further highlight that data simplification, minimal or no training, and data visualization instead of mere numbers to encourage their adoption. Additionally, they highlight that quick and dirty LCAs positively influence the design approach. Other authors confirm these preferences and usability needs (Morini et al., 2019; Suppipat et al., 2021). While simplified LCAs are preferred, no industry standard seems to be present.

4.2.3. USABILITY OF SIMPLIFIED LCA TOOLS

To gain further insight into the capabilities and usability of simplified LCA tools, four tools were selected for detailed usability analysis. These tools were selected as they were most suited to the conceptual design phase and were available for trial licenses. The tools included Sustainable Minds, IDC LCA Calculator, Fast-Track LCA Teaching Tool, and Footprint Calc. The comparison was conducted through the modeling of a simple bill of materials (BOM) with two alternatives. The BOM consisted of three to four materials, three transport processes, and three to four different end-of-life (EOL) processes. The inventory data used was derived from a master's elective course assignment at the Delft University of Technology. Unit process tables of the input can be found in **APPENDIX E**. In **Figure 12** an overview is given of what inventory is to be modelled.

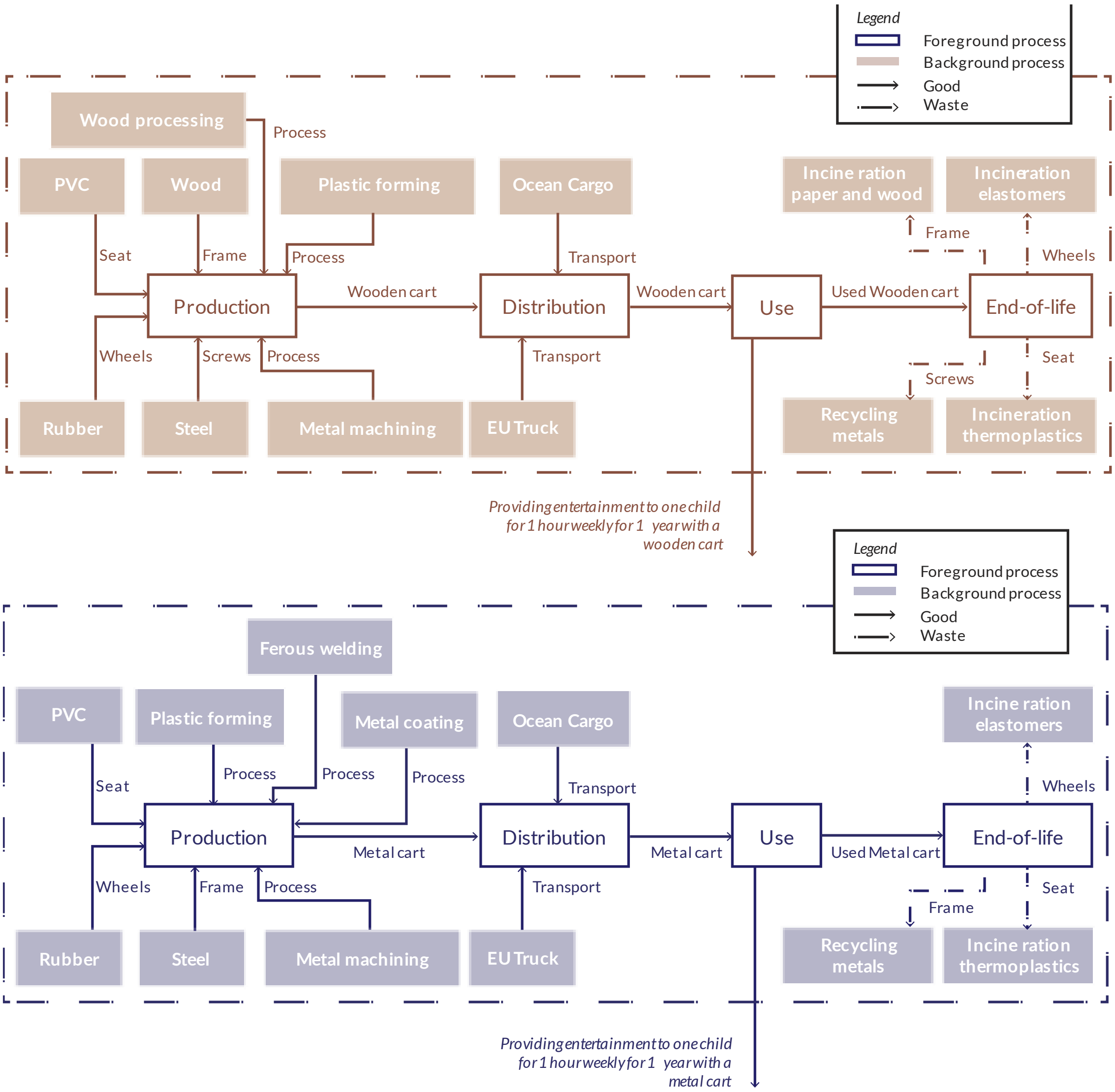


***Figure 12**. Flow charts. The top figure is flowchart for the wooden cart, and below is the flowchart for the metal cart.*

Overview of the Different Interfaces

The four simplified LCA tools varied in their interfaces and inputs required. The figures below explain and highlight the main differences. What stood out was the different ways the functional unit was defined by the tools. Additionally, all four tools had similar workflows, however, some only allowed for one alternative to be modeled, IDC LCA Calculator and FootprintCalc, while the others did allow for results comparison. The visualization of the results can be found in **Figure 13-Figure 16**

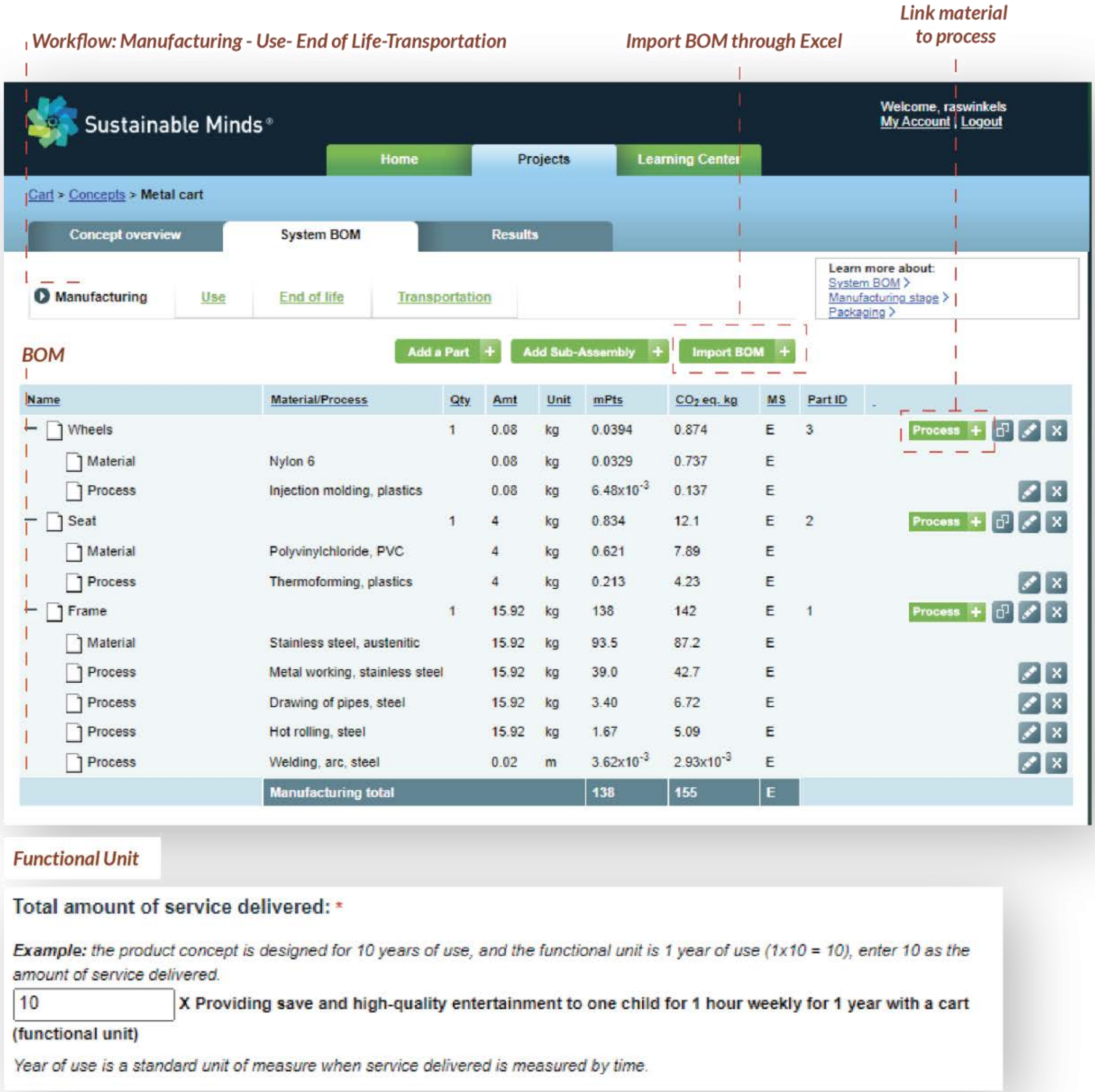


***Figure 13**. Interface Sustainable Minds (Sustainable Minds, 2024).*

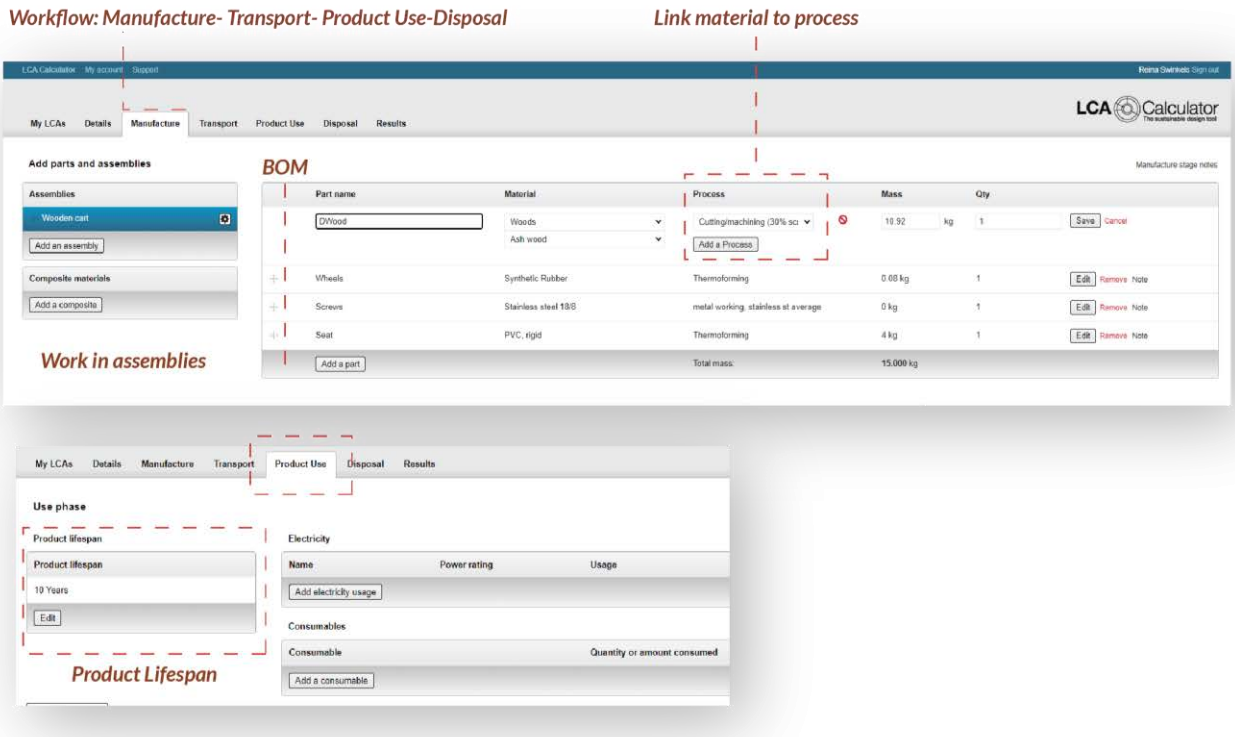


Figure 14. *Interface IDC LCA Calculator (Industrial Design Consultants, 2024).*

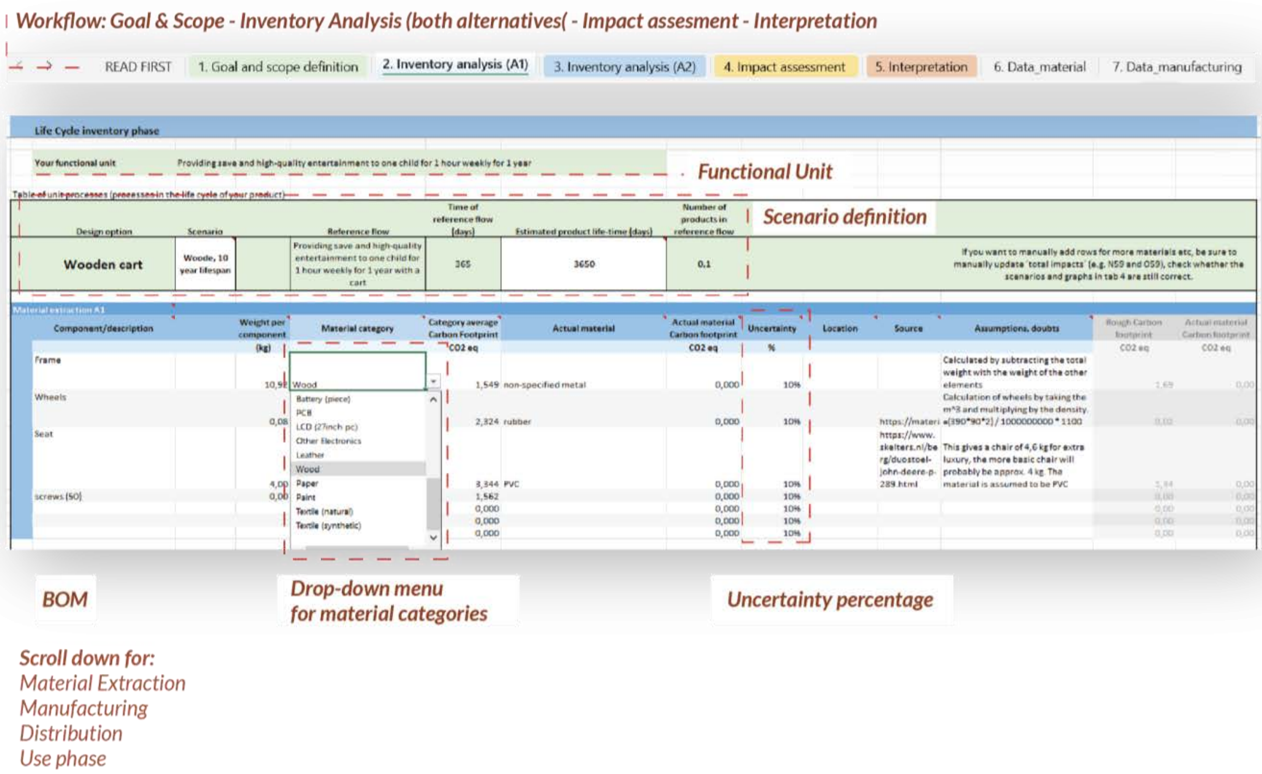


Figure 15. *Interface Fast-Track LCA Teaching Tool (de Groot, 2023).*

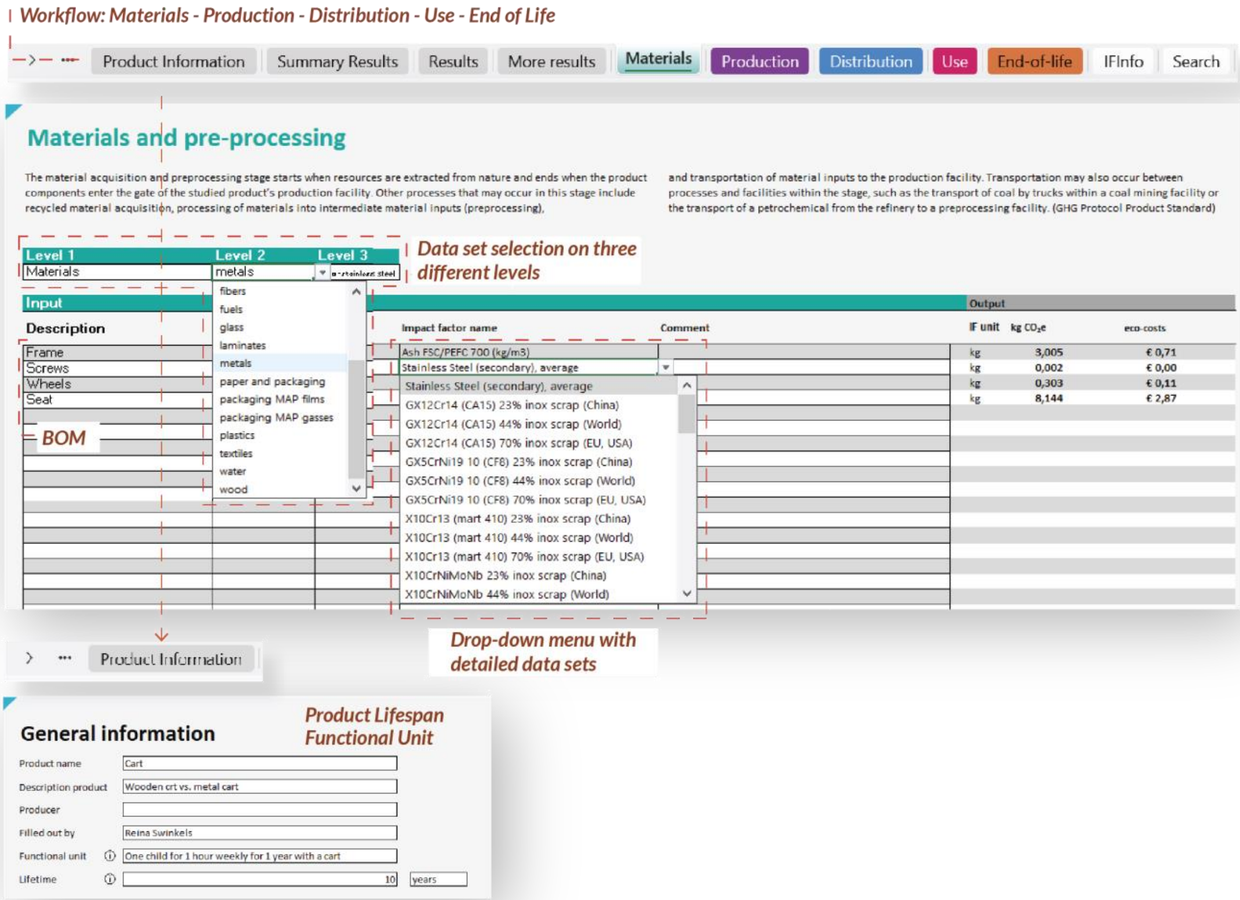


***Figure 16**. Interface FootprintCalc (The Footprinters, 2024).*

The analysis was based on the following categories: ease of use, data quality, fit into the conceptual design phase, and quality of result comparison (see **section 2.3.3**). It is important to note that the fulfillment of each category for each tool was determined based on experience, information, and the level of expertise needed to comprehend and operate the tool.

Ease of Use

The time required to complete the analysis exhibited considerable variation among the tools. The most expeditious tools were Sustainable Minds and the IDC LCA Calculator, with approximate completion times of 30 and 20 minutes, respectively. Both tools offered straightforward workflows with minimal complexity, which contributed to a user-friendly experience. In contrast, the Fast-Track LCA Teaching Tool and Footprint Calc required a greater investment of time to complete, with an average of 90 and 45 minutes, respectively. This was attributed to their more comprehensive workflows. The Fast-Track LCA Teaching Tool comprised a greater number of steps, as it followed the LCA ISO 14040 & 14044 (2006) framework in a step-by-step manner. In particular, the additional time required for the tool was due to the necessity of defining the goal and scope in depth, as well as the need to provide a section for interpreting the results. The Footprint Calc exhibited a particularly complex workflow, necessitating additional clicks for each data selection. As illustrated in **Figure 16**, the tool entailed a distinctive workflow, necessitating the selection of three distinct data levels for each modeled item. Furthermore, the data was not linked to the corresponding units, resulting in the need for manual input of this information, which further complicated the modeling process. Consequently, the workflow was more straightforward in the initial two tools, as they required fewer steps and offered more intuitive interfaces.

Every tool provided the capability to model most of the inventory and the entire product lifetime. An exception was observed with the IDC LCA Calculator, which only permitted the selection of landfill or recycling as EOL options, excluding incineration. Two tools specifically requested input from the functional unit: Sustainable Minds and the Fast-Track LCA Teaching Tool. For both tools, the functional unit also influenced the calculated results. While the IDC LCA Calculator and the Footprint Calc permitted input of a product lifetime, the results appeared to be detached from this input.

Data Quality

The quality of data used in the LCA tools was of critical importance for generating accurate results. The datasets used by Sustainable Minds and the IDC LCA Calculator were provided by the organizations. However, the IDC LCA Calculator lacked transparency regarding data sources and descriptions. The datasets used by the Fast-Track LCA Teaching Tool and Footprint Calc were from the Idemat dataset, which was comprehensive and detailed, allowing for manual data input and adjustment.

Regarding uncertainty in data, Sustainable Minds required the user to indicate whether the data was an estimate, a measurement, or derived from literature. However, this was not processed into the results. Only the Fast-Track LCA Teaching Tool allowed for the inclusion of data uncertainty, thereby enhancing the robustness of the tool in terms of data quality. The following guidelines are provided by the tool: "Uncertainty rubric: A 10% uncertainty is assigned for a perfect database match, a 30% uncertainty for a plausible substitution, and a 100% uncertainty for a wild guess" (de Groot, 2023). The uncertainties were translated into faded bars when presenting the results, see **Figure 19.**

Early Design Phase Fit

The Sustainable Minds tool and the IDC LCA Calculator were particularly well-suited for rapid, high-level assessments. The simplicity and speed of these tools made them ideal for conceptual design evaluations. However, their limited complexity meant that they were best suited for simple use cases and EOL scenarios, particularly those where only electricity use data was required and the processes involved were standardized, such as recycling, landfill, or, for Sustainable Minds, incineration. The link between materials and their associated processes facilitated the assessment process.

The Fast-Track LCA Teaching Tool was more comprehensive and enabled scenario analysis, making it well-suited for more nuanced and thorough early-stage assessments. Furthermore, the capacity to accommodate data uncertainty rendered it a robust tool, though it demanded a greater investment of time and effort. Although the process was relatively time-consuming, the ability to select grouped material categories greatly streamlined the modeling process. The Footprint Calc also permitted scenario modeling. While the Fast-Track LCA Teaching Tool required input for every scenario separately, the Footprint Calc allowed for data substitution in Excel. This allowed the user to quickly assess different data options per data input. However, the additional steps for data input, as well as searching in the extensive dataset, resulted in a slower assessment process.

Results Comparison

While the Fast-Track LCA Teaching Tool required the selection of a characterization family, the results presented were only CO2-equivalent. The IDC LCA Calculator presented the results in terms of CO2 emissions over the entire lifetime of the product. This showed that although these tools were promoted as LCA tools, they could be better categorized as carbon footprint tools. Additionally, the Sustainable Minds tool presented the results in terms of the Sustainable Minds impact categories, like ReCiPe, or CO2-equivalent per functional unit. The Footprint Calc provided the broadest impact assessment, as it could calculate the eco-cost, cumulative energy demand, ReCiPe midpoint, endpoint, and single indicator. It also gave the option to calculate the EF3.1 characterization family, however, it did not provide any results.

Both the IDC LCA Calculator and Sustainable Minds provided a comparative contribution analysis and separate results per alternative, as seen in

Figure 18 and **Figure 20.** A great strength of the Fast-Track LCA Teaching Tool was its ability to include uncertainties in the results through separate bar charts and the inclusion of a qualitative interpretation section. Additionally, the Fast-Track LCA Teaching Tool included features for scenario development, allowing for the evaluation of different lifetimes and data choices. These scenarios complicated the comparison of the alternatives, as the scenario comparison was more extensive. For instance, the contribution analysis was done separately per alternative but did compare the scenarios side by side, see **Figure 19**. Notably, this tool did not provide tables as results, making it difficult for users to interpret the exact data differences.

The scenarios of the Footprint Calc were displayed differently. The substitution of different data sources was done in a separate tab from the inventory analysis. Additionally, the results of the scenarios had their tab in Excel and were shown in a table with a percentage of reduction or increase for carbon footprint and eco-cost, see **Figure 20**. Furthermore, the Footprint Calc presented results in pie charts and tables, detailing the contributions of each lifecycle stage. However, the Footprint Calc did not provide an alternative comparison, requiring the use of two different Excel sheets to compare alternatives.

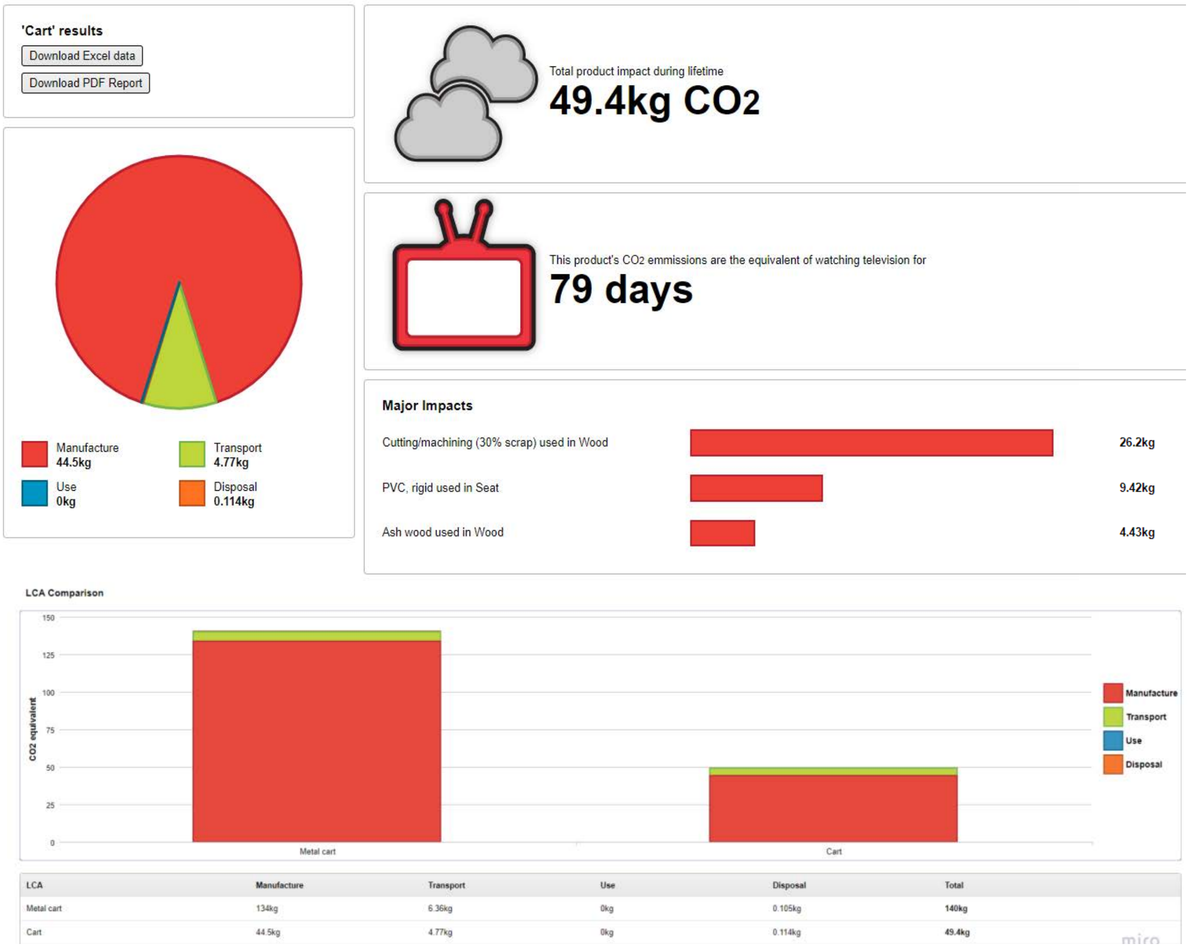
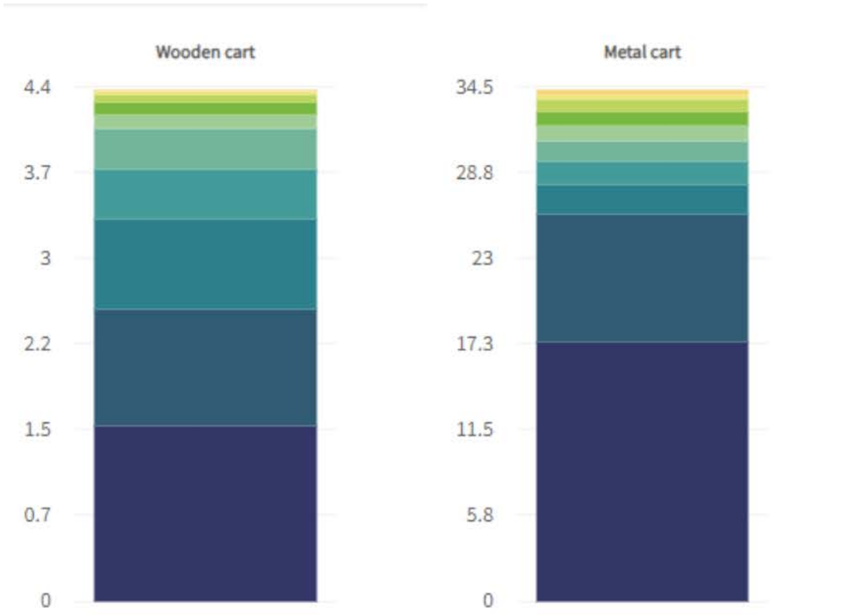


__Figure 17.__ Results provided by the IDC LCA Calculator(Industrial Design Consultants, 2024).



Total = 4.4 CO_2 eq. kg/func unit

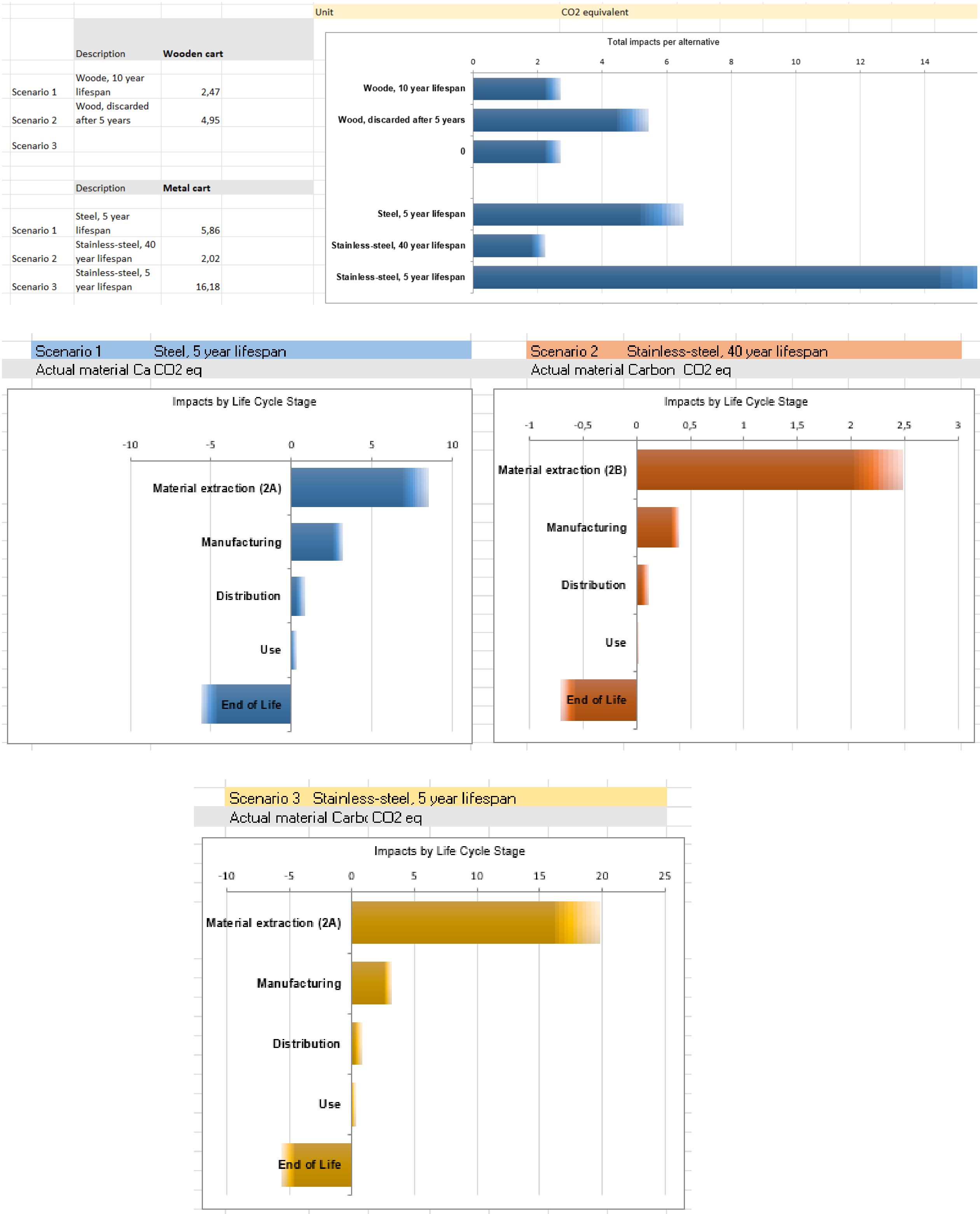
Input	CO_2 eq. kg/func unit
Material - Ash	1.52
EOL - Polyvinylchloride, PVC: Incineration, polyvinylchloride	1.00
Material - Polyvinylchloride, PVC	0.789
Process - Polyvinylchloride, PVC: Thermoforming, plastics	0.423
Transportation - Freighter, oceanic	0.358
Transportation - Truck, 3.5-7.5t	0.111
Transportation - Truck, 3.5-7.5t	0.107
Material - Nylon 6	0.0737
EOL - Nylon 6: Incineration, plastics, mixture	0.0189
Process - Nylon 6: Injection molding, plastics	0.0137

Total = 35 CO_2 eq. kg/func unit

Input	CO_2 eq. kg/func unit
Material - Stainless steel, austenitic	17.4
Process - Stainless steel, austenitic: Metal working, stainless steel product manufacturing	8.55
EOL - Polyvinylchloride, PVC: Incineration, polyvinylchloride	2.01
Material - Polyvinylchloride, PVC	1.58
Process - Stainless steel, austenitic: Drawing of pipes, steel	1.34
Process - Stainless steel, austenitic: Hot rolling, steel	1.02
Transportation - Freighter, oceanic	0.954
Process - Polyvinylchloride, PVC: Thermoforming, plastics	0.845
Transportation - Truck, 3.5-7.5t	0.296
Transportation - Truck, 3.5-7.5t	0.285

miro

***Figure 18**. Results provided by Sustainable Minds (Sustainable Minds, 2024).*



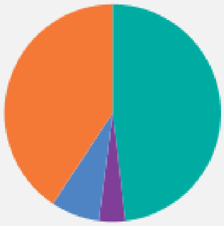
	Description	Wooden cart
Scenario 1	Woode, 10 year lifespan	2,47
Scenario 2	Wood, discarded after 5 years	4,95
Scenario 3		
	Description	**Metal cart**
Scenario 1	Steel, 5 year lifespan	5,86
Scenario 2	Stainless-steel, 40 year lifespan	2,02
Scenario 3	Stainless-steel, 5 year lifespan	16,18

Figure 19. *Scenario results provided by the Fast-Track LCA Teaching Tool (de Groot, 2023).*

Total carbon footprint	23,805	kg CO_2e
Total eco-costs	€ 5,68	
Carbon footprint	2,380	kg CO_2e / year
Eco-costs	€ 0,57	per year

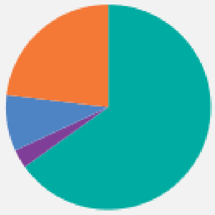
Carbon footprint

	kg CO_2e	
Materials	11,454	48%
Production	0,929	4%
Distribution	1,740	7%
Use		
End-of-life	9,682	41%
Total	23,805	



Eco-costs

	Eco-costs	
Materials	€ 3,70	65%
Production	€ 0,17	3%
Distribution	€ 0,50	9%
Use		
End-of-life	€ 1,31	23%
Total	€ 5,68	



Scenario1

	Carbon footprint			Eco-costs		
	original	scenario	Reduction	original	scenario	Reduction
Materials	11,454	11,454		€ 3,70	€ 3,70	
Production	0,929	0,523	44%	€ 0,17	€ 0,10	42%
Distribution	1,740	1,740		€ 0,50	€ 0,50	
Use	0,000	0,000		€ 0,00	€ 0,00	
EndOfLife	9,682	9,682		€ 1,31	€ 1,31	
Total	23,805	23,398	2%	€ 5,68	€ 5,61	1%

Figure 20. *Results provided by the FootprintCalc (The Footprinters, 2024).*

4.3. FACTORS INFLUENCING EARLY-STAGE DECISION-MAKING ON CIRCULAR DESIGN STRATEGIES

This section presents the challenges and the contextual factors influencing the integration of environmental sustainability into the early stages of the design process. Following this, the many challenges faced by designers are discussed, along with enablers and strategies for overcoming these barriers. As outlined in Sub-RQ3, understanding these challenges and contextual factors is necessary for developing effective solutions that facilitate circular and environmentally beneficial decision support during the conceptualization phase.

4.3.1. BARRIERS

One of the primary barriers in integrating environmental sustainability into the conceptual design phase is the financial considerations involved. The costs associated with implementing environmentally sustainable practices, including research and development expenses and systemic changes, present significant barriers (Rossi et al., 2016). Particularly for small and medium-sized enterprises (SMEs), the lack of financial incentives poses substantial challenges, as the upfront investment costs for circular materials or environmental sustainability assessment tools are perceived as high (Hanes-Gadd et al., 2023; Kirchherr et al., 2018). The adoption of circular business models offers the potential for financial returns, emphasizing the benefits of such models despite financial constraints (Bocken et al., 2016).

Additionally, the cultural barriers within the industry form a significant obstacle. Organizations are stuck in their linear system and are hesitant to change. The close involvement and willingness of stakeholders in the transition to circular practices is necessary, for instance in the costs of reverse logistics and alterations to supply chains (Hanes-Gadd et al., 2023). Furthermore, industries perceive little interest from consumers on environmental matters (Kirchherr et al., 2018). Where there is interest, there is little way of indicating the circularity or environmental benefits of a product, as there is a lack of standardized communicative sustainability indicators that include circularity of products and services (Kristensen & Mosgaard, 2020).

4.3.2. DRIVERS

Despite these barriers, several factors are driving the integration of environmental sustainability into the early stages of the design process. Legislative measures such as the Eco-design Directive and the EU Action Plan for the CE, as discussed in **section 1.1.3.**, have a significant impact by providing a regulatory framework that encourages environmentally sustainable practices (Baldassarre et al., 2020; European Commission, 2022; Hanes-Gadd et al., 2023). Additionally, the increased reporting requirements from the EU such as the CSRD for large-scale companies and the upcoming DPP for specific product categories obligate the use of environmental sustainability assessment methods within companies. In addition, increasing customer demand and pressure on organizations to prioritize environmental sustainability highlights the need to integrate environmental considerations into design decisions (Bey et al., 2013; Hanes-Gadd et al., 2023). Overcoming the cultural barriers, there is a growing momentum in research and collaborative efforts, coupled with internal motivations from within the organizational culture, further driving the momentum towards sustainable design practices (Hanes-Gadd et al., 2023; Mhatre et al., 2021).

4.3.3. CHALLENGES

Environmental Sustainability in Organizations

Principles of environmental sustainability and circularity are frequently overlooked within companies, particularly at the early stages of a project (Dekoninck et al., 2016; Peace et al., 2018; Company B (see **Table 4**)). One of the primary challenges in implementing sustainable development within business practices is translating environmental benefits into tangible business incentives. This issue has been identified by numerous researchers, including Faludi et al. (2020) and Rossi et al. (2016). Designers often struggle to prioritize environmental requirements alongside traditional product requirements, making it challenging to balance these competing demands (Dekoninck et al., 2016; Kravchenko et al., 2020; Rossi et al., 2016; Watz & Hallstedt, 2022).

(Rigamonti & Mancini, 2021) discovered that the majority of their circularity assessments and LCA studies yielded contradictory outcomes, largely due to the disparate requirements and measurement methods employed. Such contradictory results further complicate the decision-making process, especially when aiming to develop a circular and environmentally sustainable product (Kravchenko et al., 2020). Therefore, designers often experience trade-offs between environmental sustainability and circularity objectives (Hanes-Gadd et al., 2023; Kravchenko et al., 2020).

A significant obstacle to implementing environmentally benign circular strategies is the lack of knowledge within organizations. The field of environmental sustainability is broad and complex, making it challenging for companies to identify appropriate starting points, relevant metrics, and effective methods for quantifying impacts (Faludi et al., 2020; Hallstedt, 2017; Kravchenko et al., 2020). General environmental knowledge is essential for interpreting results and making informed decisions. This issue is highlighted in an interview with Company A (see **Table 4**), where it was noted that while designers ideally in their company make decisions and assessments independently, they often require the expertise of sustainability departments. This highlights the necessity for multidisciplinary teams around the designer with knowledge of environmental sustainability. Literature supports this, stating that understanding the expert knowledge of the LCA theory and its terminology is crucial for interpreting results and making the right decisions (Peace et al., 2018; Rossi et al., 2016; Villamil & Hallstedt, 2018).

The absence of environmental sustainability expertise in key positions further amplifies this issue (Dekoninck et al., 2016; Faludi et al., 2020; Villamil et al., 2023). Even when experts are available, determining how and where to involve them effectively can be challenging (Dekoninck et al., 2016). Additionally, there is often a lack of mutual understanding within organizations, leading to varied interpretations of circularity and environmental sustainability (Hanes-Gadd et al., 2023) The selection of new materials based on environmental performance also requires input from suppliers, who may lack the necessary information. This process requires additional research and the acquisition of new databases, which can be expensive (Hanes-Gadd et al., 2023).

The availability of tools and methods

The current landscape of tools and methods for environmental sustainability assessment is another area filled with challenges. The excessive availability of tools and methods presents a challenge for companies seeking to identify those that align with their specific requirements (Dekoninck et al., 2016; Faludi et al., 2020; Peace et al., 2018 Company A; Company B). For instance, during an interview with Company A, it was proposed that tools should be adaptable to accommodate the diverse needs of companies: *"Maybe the tool should be made to fit every company. Say we deliver a standard tool with some to-dos for the sustainability department in the company. For instance, weighting & finding best practice examples."* Additionally, as experience in **sub-chapter 4.2** has shown, that finding the right tool between all the different variants can be challenging and requires effort. It is often necessary to have prior experience and training to use environmental sustainability assessment tools effectively, which many organizations lack. (Rossi et al., 2016; Villamil et al., 2023b; Villamil & Hallstedt, 2018)

Consequently, a significant proportion of companies have determined that existing tools are unsuitable for their practices. As a result, they have developed their own tools, methods, or guidelines (e.g., Company A; Company B , Faludi et al., 2020; Hallstedt, 2017; Hanes-Gadd et al., 2023; van Dam et al., 2017). Some practitioners have created simplified spreadsheet interfaces or customized tools to facilitate usage within their organizations (Peace et al., 2018). While these self-developed tools can be tailored to specific needs, they are often subject to limitations, for instance in scope or standardization requirements, which can affect the accuracy and reliability of the assessments.

The rigid nature of academic methods is often mismatched with the practical needs of designers (Dekonninck et al., 2016). Additionally, aspects like frequent errors or bugs within the tool further hinder the use of tools (Peace et al., 2018). Moreover, the translation of tool outputs into actionable recommendations can be challenging due to a lack of transparency in the calculation of these outputs (Kravchenko et al., 2020; Peace et al., 2018). Furthermore, the complexity, over-formalization, and low usability of many tools further hinder their adoption (Rossi et al., 2016; Villamil et al., 2023b). For example, Company C, which utilizes an external tool, namely Circular Transition Indicator (CTI) which measures the environmental impact and circular material inflow and outflow of products and companies (World Business Council for Sustainable Development, 2023), has encountered difficulties in correctly modeling aspects of the tool, leading to less accurate assessments. For instance, they incorrectly assigned biobased materials as a renewable resource according to the definition of the framework, which positively influenced the outcome of the tool. This issue aligns with prior research findings indicating the challenges in achieving full accuracy and truthfulness in modeling with simplified assessment tools (**sub-chapter 4.2).** Such findings highlight the necessity for improved tool usability and transparency to ensure more accurate assessments.

Mindset shift

The implementation of a systematic approach at an early stage of the design process requires significant effort and motivation. Generally, there is a lack of time and resources dedicated to these assessments by organizations (Hallstedt, 2017). In addition, given the resource-intensive nature circular and eco-design approaches through, for instance, implementing new business models and suppliers (Dekoninck et al., 2016; Hanes-Gadd et al., 2023), it is not feasible to make decisions as rapidly as during a traditional design process. Moreover, these decisions cannot be made by the design team alone, necessitating input from other stakeholders (Baldassarre et al., 2020).

Furthermore, the role of the designer must evolve to consider supply chain logistics, networks, and partnerships (Baldassarre et al., 2020; Hanes-Gadd et al., 2023). Despite the necessity for a collaborative approach, there is often a lack of resources to facilitate this within companies, which hinders continuous improvement on current developments (Dekoninck et al., 2016; Villamil & Hallstedt, 2018). Consequently, there is a necessity for enhanced tools that facilitate system and strategic perspectives (Villamil et al., 2023).

4.3.4. ENABLERS

To facilitate effective integration of environmental sustainability into the conceptual design phase, it is essential to identify various enablers. These enablers serve as way for overcoming barriers and challenges, empowering designers and organizations to make informed decisions aligned with circular and environmentally beneficial design principles.

Simplicity and Ease of Use

Enabling designers to adopt and utilize tools seamlessly requires enhancing simplicity and ease of use. Designers should have access to user-friendly tools that are intuitive and require minimal training (Dekoninck et al., 2016; Lindahl, 2006). Moreover, eco-design experts play a pivotal role in providing guidance and support for the implementation of sustainable practices within organizations (Dekoninck et al., 2016).

Actionability

Providing actionable insights is crucial for guiding decision-making processes effectively. Designers need tools that offer clear and actionable recommendations, facilitating the identification of practical steps for improving environmental performance (Faludi et al., 2020; Peace et al., 2018). Transparent methods allow designers to comprehend the rationale behind recommendations, fostering trust and confidence in the decision-making process (Dekoninck et al., 2016; Faludi et al., 2020).

Alignment with Business Incentives and Goals

To ensure widespread adoption and acceptance, tools must align with organizational objectives and priorities (Faludi et al., 2020). Tools that satisfy the specific requirements of companies are more likely to be adapted by companies.

Alternative Comparison

Tools should facilitate comparison between different design options by elucidating trade-offs between various requirements (Faludi et al., 2020). By providing comprehensive decision support when comparing alternatives, tools empower designers to make informed choices that balance environmental sustainability with other design considerations.

Systemic and Strategic Planning

Tools should enable designers to assess future strategic scenarios and incorporate a systemic perspective into decision-making processes (Villamil et al., 2023). By considering long-term implications and strategic objectives, designers can develop more robust and resilient design solutions that align with circular principles.

Environmental Sustainability in Policy

To drive meaningful change in environmental sustainability, it is crucial to foster willingness within an organization. This transformation necessitates not only comprehensive metrics for assessing environmental and circular performance but also a robust regulatory framework to encourage organizations and facilitate accurate and transparent results.

Interdisciplinary Collaboration

Encouraging interdisciplinary collaboration within organizations can enhance the integration of environmental sustainability into design processes. Engaging experts from various fields, including environmental science, engineering, and business, can provide diverse perspectives and foster innovative solutions that address sustainability challenges effectively (Baldassarre et al., 2020; Villamil et al., 2023).

5.

PROGRAM OF REQUIREMENTS

The previous chapters examined the designer's workflow and the various environmental sustainability assessment methods and tools employed in industry. It was established that the designer's workflow relies heavily on intuition and creativity during the conceptualization phase of the design process. However, the research suggests that the current analytical LCA tools clash with the designers' attitude during this phase. It is therefore recommended that to integrate LCA tools into the designer's workflow, the tools facilitate creative processes and fast-paced assessments.

The eco-design methods found to evaluate circular design strategies implement both qualitative and quantitative environmental sustainability assessment approaches. Although comprehensive frameworks such as LCP, STARDUST, and BECE framework offer a systemic perspective by integrating long-term planning and scenario analysis, their inherent complexity restricts their applicability in the early stages of design. Nevertheless, they offer invaluable insights regarding the environmental sustainability assessment of different circular design strategies

Furthermore, the previous chapter examined LCA-based tools, which were classified into three categories: full-scale software, simplified tools, and CAD-integrated solutions. Although full-scale software offers comprehensive analysis, it necessitates a high level of expertise, rendering it unsuitable for expedient assessments. In contrast, simplified tools offer usability for conceptual design stages, but may result in a compromise in data quality. This emphasizes the necessity for a balance between ease of use and accuracy in environmental sustainability assessment tools.

Designers encounter difficulties when integrating environmental considerations into their work. These include the translation of environmental benefits into business value, the balancing of sustainability with traditional product requirements, and the management of trade-offs between environmental and circularity goals. The lack of expertise within organizations, coupled with the diverse interpretations of circularity and the difficulty in selecting appropriate tools, further impedes progress. The complexity and lack of user-friendliness of existing tools restrict their efficacy in practical design contexts.

To address these challenges, this chapter proposes a program of requirements for the development of an effective environmental sustainability assessment tool. The objective of this framework is to bridge the gap between complex academic methods and the practical needs of designers by focusing on simplicity, alignment with business goals, and actionable recommendations. The proposed tool will be user-friendly, accurate, and adaptable to diverse organizational contexts, thereby empowering designers to make informed early-stage decisions regarding environmental sustainability and circular design strategies.

5.1. PROGRAM OF REQUIREMENTS

To establish the program of requirements, this research's findings were compiled into an extensive list of criteria to be implemented into the tool. This section explains each requirement category and the related findings. Additionally, for some requirements, examples are given to illustrate how these requirements could potentially be integrated. **Table 9** provides a summary of the essential (must-have) requirements. **APPENDIX F** provides a detailed overview of all requirements, including desirable and possible requirements, with an additional explanation of each requirement and its origin.

***Table 9**. Must haves in the program of requirements.*

Category	Section	Nr.	Requirement
1. Use & Usability	1.1 User	1.1.1	Designers should have limited access to only the necessary functions.
		1.1.2.	Environmental sustainability experts should have access to more advanced functions.
	1.2. Interface usability	1.2.1.	The interface should be clean and visually pleasing.
		1.2.2.	The interface should be intuitive and feel familiar to users.

		1.2.3.	The homepage should provide a quick overview of the necessary steps.
		12.4.	The interface should provide visual feedback for errors and successes.
	1.3 Workflow	1.3.1	Modeling a simple BOM should take a maximum of 45 minutes.
		1.3.2.	The tool should function effectively with limited data availability.
		1.3.3.	The tool should facilitate concept selection.
		1.3.4.	The tool should facilitate brainstorming sessions.
2. Knowledge & Training	2.1 Familiarity	2.1.1.	Translate LCA terms into design terms for clarity.
		2.1.2.	Descriptions should be clear and direct.
		2.1.3.	Limit the use of LCA jargon.
	2.2. Training	2.2.1	The tool should quickly make designers feel experienced with its use.
		2.2.2	Training should be simple and not intense, with a maximum duration of 15 minutes.
		2.2.3.	The tool should provide detailed information on all functions for the sustainability expert to understand.
3. Data	3.1 Quality	3.1.1	Ensure transparency in data sources.
		3.1.2.	Provide an up-to-date database and inventory data and scenarios.
		3.1.3.	Ensure data is updated regularly to reflect the latest research and industry practices in eco-design and circular design.
	3.2. Accessibility	3.2.1.	Clearly indicate the source of data within the database.
		3.2.2.	Allow users to access the full database and search through it
		3.2.3.	Link materials and processes to each other.
		3.2.4.	Allow for addressing uncertainties and assumptions in data.
		3.2.5.	Allow for addressing assumptions on design parameters
		3.2.6.	Allow users to be able to upload their own data (Excel).
	3.3. Flexibility	3.3.1	Provide material categories.
		3.3.2.	Allow users to input company-specific data.
4. Organizational Alignment & Actionable Results	4.1. Incentives	4.1.1	Allow organizations to input their environmental sustainability goals.
		4.1.2.	Provide quantitative feedback on how each alternative helps achieve these goals.
		4.2.1	Provide a wide range of visualized results.

	4.2. Actionable results	4.2.2.	Allow detailed contribution analysis.
		4.2.3.	Provide life cycle phase contribution analysis.
		4.2.4.	Enable side-by-side comparison of alternatives and scenarios.
		4.2.5.	Display data uncertainties in the results.
	4.3. Flexibility & adaptability	4.3.1.	Allow environmental sustainability experts to choose impact assessments.
		4.3.2.	Allow environmental sustainability experts to model additional life cycle phases.
		4.3.3.	Implement a system for regular updates and improvements based on user feedback and advancements in environmental sustainability practices.
5. LCA	5.1. General	5.1.1	Should perform be able to perform as a full and simplified LCA.
		5.1.2.	Assess according to the ISO framework.
		5.1.3	Integrate ex-ante LCA aspects to assess future resource constraints and technological innovations.
	5.2 Goal and scope definition	5.2.1	Minimize the amount of input needed before starting the analysis.
		5.2.3	Environmental sustainability experts should define the scope, including future scenarios and impact assessment choices.
		5.2.4	Define the functional unit by asking questions like "what does your product or service provide?"
	5.3. Inventory analysis	5.3.1	Allow for modeling different life cycle stages.
		5.3.2	Enable the use of unit process data from a repository.
		5.3.3	Link processes and materials.
		5.3.4	Set the geographical location for production.
	5.4. Impact assessment	5.4.1	Impact assessments should be selected by the sustainability expert.
		5.4.2	Allow for multiple options, in line with regulations.
		5.4.3	Provide a wide range of visualized results.
	5.5. Interpretation	5.5.1	Allow the user to test assumptions through sensitivity analysis.
		5.5.2	Enable the user to reflect on data through consistency check questions.
		5.5.3	Encourage the user to think about the completeness of the results through specific questions.
6. Circular Design	6.1. Modeling circularity	6.1.1.	Allow for modeling different lifetime scenarios and use cycles. Provide the user with allocation options.

		6.1.2.	After selecting strategies, ask for additional input data, such as the production of additional parts and their frequency of use for the functional unit.
	6.2. Qualitative features	6.2.1.	Assist the designer with qualitative forms of assessment for circular aspects such as ease of disassembly.
7. Other	7.1. Regulatory Compliance	7.1.1	Ensure the tool is updated to comply with the latest regulations and standards in environmental sustainability and CE practices.
		7.1.1	Implement a process for regularly reviewing and updating the tool to align with new regulations and industry standards.
	7.2. Data security	7.2.1.	Ensure data privacy and security measures are in place to protect sensitive company information.
		7.2.2.	Implement access controls and encryption for data storage and transmission.

5.1.1. USER & USABILITY

One of the principal challenges identified was the lack of knowledge among designers regarding the conduct of LCAs. As this limitation cannot be readily addressed, it is suggested that designers should leverage the expertise available within the design team. Therefore, the tool should permit input from environmental sustainability experts, who can provide the primary assessment settings and additional modeling if required. Consequently, a primary user requirement is the necessity to restrict access for different user roles. Designers should have limited access, restricted to only necessary functions (*Requirement 1.1.1*). This limitation is designed to streamline user interaction with the tool, preventing unnecessary complexity that could hinder productivity. Tasks requiring higher expertise, such as advanced modeling or impact assessment selection, are reserved for environmental sustainability experts (*Requirement 1.1.2*). This division optimizes workflow efficiency, ensuring each user type focuses on tasks aligned with their skill set, thereby maximizing the tool's utility in real-world applications. Environmental sustainability experts are granted broader access to advanced functions within the tool.

The main objective of the interface design is to facilitate rapid comprehension and decision support, allowing designers to navigate the tool effortlessly and focus on creative problem-solving rather than learning complex navigation systems. This objective was formed from understanding how designers make decisions during the conceptualization phase, as they make fast and intuitive decisions based on prior experiences (System 1, see **section 3.2.1**). Therefore, the interface should provide familiarity and intuitiveness (*Requirement 1.2.2*). By mimicking well-known design patterns and workflows, the tool reduces cognitive load, enabling designers to leverage their intuitive thinking effectively. Visual feedback mechanisms are also essential, offering immediate notifications for errors and validation.

The workflow requirements focus on optimizing efficiency and integration with existing design processes. The tool should facilitate streamlined processes for tasks like modeling a BOM or conducting early-stage concept ideation. For instance, ensuring the inventory analysis can be performed in under 45 minutes ensures that initial assessments remain efficient and quick (*Requirement 1.3.1*).

5.1.2. KNOWLEDGE AND TRAINING

A key objective is to translate complex LCA terminology into more familiar design terms (*Requirement 2.1.1*). This approach ensures designers can rapidly understand and apply environmental sustainability metrics within their projects. For instance, the term "alternatives" in LCA is equated to "concepts" in design theory. Moreover, BOMs can help understand the Inventory Analysis stage of LCA. While BOMs list product components and details, they typically exclude logistics, energy use, and EOL aspects. During the conceptualization phase, BOMs provide designers with an overview of components and concepts while communicating progress and changes within the design team (Clarkson & Eckert, 2005). Tools such as Sustainable Minds and the IDC LCA Calculator facilitate effective communication and fast comprehension of environmental impacts during design evaluations.

A further set of requirements focuses on the learnability and training of the tool. Within a design team, it is expected that knowledge is present on the basic elements of an LCA. Nevertheless, designers should be able to use the tool during ideation sessions and quickly evaluate design decisions, understand the interface, and interpret results accordingly. To ensure designers quickly become comfortable with the tool, training should take a maximum of 15 minutes to understand the basics (*Requirement 2.2.2*). This ensures designers can use the tool rapidly and feel experienced with it, following elements from the intuitive thinking of designers (System 1) for rapid insights and preliminary evaluations. In instances where more detailed analysis is required, supplementary training should be provided by the tool provider or through environmental sustainability expertise within the company, complementing subsequent analytical approaches (System 2) at a later stage in the design process.

5.1.3. DATA

A fundamental requirement is ensuring transparency in data sources (*Requirement 3.1.1*). This necessitates indicating where the data originates from within the tool's interface. Transparency is crucial for users to trust the results derived from these tools, especially considering the complexity of simplified LCA models, which can obscure data origins if not properly managed.

Maintaining an up-to-date database is essential to keep the tool relevant for companies (*Requirement 3.1.2*). Regular updates must be implemented to incorporate advancements in eco-design and circular design practices. This ensures the data accurately reflects current industry standards and scientific research, enhancing the tool's credibility and relevancy in practical settings.

Moreover, tools must facilitate easy access to their databases, allowing users to search and retrieve relevant materials and processes efficiently (*Requirement 3.2.2*). This includes functionalities like keyword searches within databases, which streamline finding specific datasets. Linking materials and processes within the tool enhances accessibility, as demonstrated by the Sustainable Minds and IDC LCA Calculator, enabling seamless selection and integration of data points during assessments (*Requirement 3.2.3*).

Flexibility in the tool design is critical to accommodate various user and organizational needs. Incorporating company-specific data ensures tools can adapt to unique organizational requirements, such as incorporating data from preferred suppliers or newly developed materials (*Requirement 3.3.2*). Additionally, The Fast Track LCA Teaching tool allowed users to select clustered data for material categories such as "wood" or "steel". This simplifies the modeling of BOMs, which is particularly beneficial when designers are unsure about specific material choices (*Requirement 3.3.1*).

5.1.4. ORGANIZATIONAL ALIGNMENT AND ACTIONABLE RESULTS

To translate environmental aspirations into actionable design decisions effectively, it is valuable to focus on existing company-specific environmental sustainability targets. The proposed tool addresses this by facilitating the incorporation of company-defined environmental targets (*Requirement 4.1.1*). The sustainability expert can input quantitative targets and select the relevant impact categories. For instance, a company seeking to reduce its production-related water consumption by 10% can input this target, relating it to the impact category “water use.” The tool would then identify the most effective design alternatives for achieving this goal (*Requirement 4.1.2*). Similarly, a company aiming to decrease its carbon footprint by a certain percentage could input this target, selecting the impact category "climate change," enabling the tool to identify design options with the greatest potential for CO2-eq emissions reduction. This targeted approach allows companies to make design choices directly aligned with their established environmental sustainability objectives. Additionally, it fosters continuous awareness among designers regarding these objectives and the contribution of their design choices to their achievement.

To facilitate the adoption of the proposed tool in various business contexts, the tool must be designed to generate comprehensive, intuitive, and accessible outcomes (*Requirements 4.2.1 – 4.2.4*). This requires a range of visualizations tailored to specific assessment goals. The tool should facilitate in-depth contribution analyses, comparisons between alternative design options, and rapid identification of significant environmental impact contributors within the product. Facilitating actionable results with rapid hotspot identification is crucial for the designers' workflow, enabling designers to utilize the tool during the conceptualization phase, where intuitive and fast, System 1, thinking is predominant.

Displaying data uncertainties is crucial for transparency and accurate result interpretation *(Requirement 4.2.5).* The Fast Track LCA Teaching Tool by de Groot (2023) employs faded bars or confidence bands to illustrate uncertainties. In the Fast-track LCA Teaching Tool, uncertainties are provided by the user in percentages. The proposed tool in this research takes this aspect further by allowing the user to input assumptions regarding design parameters, including uncertainties related to weight or quantities. These uncertainties can be represented as faded bars or confidence bands. Additionally, the tool's modeling incorporates several assumptions. For instance, during the modeling of circular design strategies, input will be required for the expected partial outflow and replacement of products. This data is often based on assumptions and should be clearly stated in the results panel, allowing designers to interpret the reliability of their assessments and make informed decisions accordingly.

5.1.5. LIFE CYCLE ASSESSMENT

For the requirements stated concerning the accurate implementation of the LCA framework, the main points are derived from established standards (ISO 14040, 2006 ; ISO 14044, 2006) and the LCA handbook (Guinée, 2002)(*Requirement 5.1.2)*. During the goal and scope phase, the tool should allow for a rapid and efficient process, minimizing the number of steps and providing guidance on the formulation of the functional unit using questions. During the inventory analysis, the tools must facilitate the modeling of different life cycle stages and effectively link processes and materials. In addition, the tool should provide visual feedback of the modeling process through the creation of a flow diagram per alternative. This flow diagram allows designers to visually see their modeling process, which allows them to understand what is going on. Moreover, the tool should facilitate interpretation through features such as sensitivity analysis, consistency checks, and prompts for result completeness. These functionalities empower users to analyze data robustly, validate assumptions, and make informed decisions based on reliable environmental insights.

The aim of the tool should be to provide a streamlined workflow through the LCA. Depending on the level of detail required by the user, the tool can be brought down to a simplified LCA tool (*Requirement 5.1.1.)*. The workflow should be adjustable according to the needs of the user. Say, the designer wants to quickly evaluate different decisions in a product, the tool should not require the user to go through the full ISO framework. This requirement could be fulfilled by setting up the tool in such a way that the required information is already filled in. To illustrate, the sustainability expert could have already created a project file upon starting a new project, in which they have already selected the relevant impact characterization family, set the functional unit, and implemented the data of a reference product. By doing this, the designer would be required to only make changes in the inventory or select a few circular design strategies it wishes to compare with the reference product.

Ex-ante LCA represents a fundamental component of the tool's functionality, enabling the integration of long-term perspectives and scenario development into the LCA process (Cucurachi et al., 2018). **Section 4.1.3** demonstrates the effectiveness of long-term perspectives in addressing the environmental implications of circular design strategies. The ex-ante LCA approach is employed to project future environmental impacts and facilitate strategic planning in innovative technology development, therefore capable of enhancing the evaluation of circular design strategies. Furthermore, the utilization of ex-ante LCA acknowledges the uncertainties in data during the early phases of product development (van der Giesen et al., 2020). The data in an ex-ante LCA can be estimated or derived from existing unit processes that are expected to be similar to the emerging technology. This aligns with the tool's broader objective of offering early-stage insights to support decision-making while acknowledging the inherent uncertainties of the conceptual design phase (van der Giesen et al., 2020). Subsequently, due to high data uncertainties, the results derived from ex-ante should be used to give direction for further development, rather than being viewed as analytical and robust results.

Furthermore, the application of ex-ante acknowledges the environmental sustainability assessment as an exploratory process. Instead of being analytical and robust, like a traditional LCA, the ex-ante process resembles more the design process. For instance, ex-ante LCA requires a higher level of collaboration between different experts on technology developers and other stakeholders. This is necessary to understand the context and create feasible technology roadmaps ((Cucurachi & Blanco, 2022). The ex-ante approach therefore allows the ability to create an advanced environmental screening tool for design concepts with an exploratory nature. Consequently, the incorporation of ex-ante LCA features into the tool ensures that design choices align with long-term environmental and socio-economic objectives while accounting for data uncertainties (*Requirement 5.1.2*).

How the implementation of ex-ante LCA in the tool could potentially be implemented is described in detail in the following section on circular design.

5.1.6. CIRCULAR DESIGN

The objective of the proposed tool is to evaluate the environmental impact of various design decisions. One of the decisions that the tool aims to inform is the selection of potential circular design strategies that could prove environmentally beneficial when considered in the context of the product baseline. In order to facilitate an environmental sustainability assessment of circular design strategies, it is necessary for the tool to be capable of modeling such strategies. The tool is designed to facilitate assessment through three distinct requirements. Firstly, the tool should facilitate the selection of different circular design strategies during the development of alternatives. The selection should be made in alignment with the designer's preferences regarding the circular design strategies to be investigated during the ideation phase. Once a particular circular design strategy has been selected, the tool should prompt the user to respond to a series of questions that elicit the requisite inventory information for modeling the strategy in a standardized manner (*Requirement 6.1.2).* The modeling of these circular design strategies would require the input of supplementary data for each selected strategy. For instance, when designing for repair, it is crucial to ascertain the frequency of repair, the type of spare parts to be produced, the projected increase in the product's lifespan, and the anticipated success rate of the repair.

Secondly, the tool should be capable of modeling circular strategies that encompass multiple life cycles and the extended longevity of products *(Requirement 6.1.1*). The modeling of these circular design strategies requires the allocation of environmental impacts across the various product lifetimes and use scenarios. As illustrated in **section 4.1.3**, the research conducted by Malabi Eberhardt et al. (2020) indicates that cascading environmental impacts over multiple use cycles would motivate each stakeholder to contribute towards achieving circularity within the system. This perspective is reflected in the proposed tool, which cascades environmental impacts throughout the entire product lifecycle. In light of the considerable impact that the selected circular design strategy has on the allocation, it is essential that the tool facilitates a proposed allocation approach per strategy.

Thirdly, to facilitate long-term planning and the incorporation of a systemic perspective, it is essential to incorporate elements from the ex-ante LCA method. As previously stated, this integration enables the assessment of prospective environmental impacts and the formulation of strategic plans for product lifecycle management. An ex-ante assessment allows for the evaluation of the environmental implications of circular design strategies prior to their development. One potential integration of this approach into the proposed tool would be as follows:

Consider a design project that has commenced to develop a line of circular products intended to replace traditional products by 2035. The sustainability expert initiates the process by creating a new project in the tool, defining the temporal scope as 2035, selecting the ReCiPe family as the impact assessment method, and incorporating existing data from the current product. In selecting the 2035 timeframe, the expert identifies three scenarios from a pre-existing database that are deemed to be relevant to the project. As proposed by Steubing & de Koning (2021) the database includes comprehensive inventory data and a variety of scenarios.

During the initial stages of the design process, the designer must select between two distinct options.

Alternative 1: The creation of a product comprising bio-based components may result in a reduction in the product's lifetime, yet it may also facilitate the utilization of regenerative materials. It is anticipated that bio-based technology will become 5% more energy-efficient over the next decade. The designer develops a model of the current bio-based technology, accounting for projected reductions in electricity usage.

Alternative 2: The product should be designed in such a way that it can be refurbished. The designer then estimates the frequency of reuse and the number of additional components required, employing a proxy from a similar product to partially replace the unrepairable components.

Subsequently, the tool generates results indicating the environmental impacts of the reference product and the two alternatives across the three selected scenarios. This enables the designer to evaluate and ascertain which concept exhibits the greatest potential for circularity while maintaining minimal environmental impact.

Furthermore, as previously outlined in **section 4.1.3**, a comprehensive evaluation of circular strategies cannot be based on LCA alone. Some aspects of circularity, such as product architecture, stakeholder engagement, and the influence on consumer behavior, are not readily quantifiable within the constraints of time-limited LCA. To address this limitation, it is necessary to integrate a qualitative dimension into the tool to complement the quantitative LCA outputs. The designer should be able to state assumed qualitative environmental implications, such as addressing the difficulty to repair or the product being trend sensitive. The results of the LCA can then be weighed against these assumptions. In addition, the qualitative component should serve to inform the designer and verify the achievement of specific aspects that are crucial for the implementation of the circular design strategy and the realization of correlated environmental benefits (*Requirement 6.2.1*). To illustrate, in the case of a product being redesigned for refurbishment, the tool may highlight the importance of product architecture that is readily accessible, prompting the user to confirm that the product design facilitates disassembly. Similarly, for strategies involving product-service systems or extended producer responsibility, the tool could prompt the user to consider stakeholder involvement. This could entail prompting the user to confirm plans for collaboration with repair facilities or reverse logistics providers. By incorporating these qualitative aspects, the tool would facilitate a more comprehensive evaluation of circular economy initiatives, thereby supporting informed decision-making throughout the product development lifecycle.

5.1.7. OTHER REQUIREMENTS

Furthermore, it is necessary to comply with regulations and ensure data security. These requirements are primarily driven by the demands of companies. By facilitating regulatory reporting, for instance, CSRD, . supporting the development of DPPs per product category, or the providing the up-to-date PEF impact category (see **section 1.1.3**), the tool can be more readily implemented in practice (*Requirements 7.1.1 & 7.1.2*). Additionally, as the tool will handle company-sensitive data, such as the exact material choices or production locations, it must be able to handle this data securely (*Requirements 7.2.1 & 7.2.2.)*.

5.2. STRUCTURE AND USE

The requirements aim to serve as the foundation for the development of a new tool. This sub-chapter presents an illustrative example of how the requirements could be integrated into a tool, accompanied by a specific use scenario.

5.2.1. INTEGRATION OF REQUIREMENTS

The identified requirements are integrated into a cohesive framework to ensure that the new tool meets the needs of designers, aligns with business goals, and provides actionable insights. This integration begins with a focus on simplicity and ease of use. The environmental sustainability assessment tool is intended for use by designers and environmental sustainability experts in various stages of the product design process, particularly in the early stages where critical decisions impact the overall environmental footprint.

Based on the categorized requirements, the specific features and functionalities of the tool include an intuitive and user-friendly interface with clear navigation, visual input forms, and graphical output displays. Integrated training modules and user support resources, along with contextual help and tutorials embedded within the tool, enhance the user experience and accessibility. The tool manages data efficiently by providing generalized data inputs with options for specific data entry and maintaining a repository of process models and scenarios for reuse. The output formats include diagrams, graphs, and detailed reports, with clear and actionable recommendations based on assessment results. Systemic and strategic planning are integral to the framework. The tool incorporates ex-ante LCA to assess future societal and technological scenarios, providing consistent scenarios with different likelihoods. It includes features for long-term strategic planning and scenario analysis, helping companies prepare for future challenges and align their strategies with long-term goals.

5.2.2. USE SCENARIO

The tool is designed to be integrated at the start of a new project, when a concept for a type of product and the projected market launch timeline have been established. At this stage, the environmental sustainability expert incorporates the company's environmental sustainability targets and considers presumed scenarios for the product's development phase.

Once set up, the tool is provided to designers as an ideation tool, helping them identify which circular strategies are most beneficial for the product. To utilize the tool, designers or sustainability experts must input a basic concept of the product, including estimates for the expected materials, their mass, and the product's lifetime. The tool then generates actionable results, indicating which circular strategy offers the lowest environmental impact.

Additionally, the tool evaluates how well the product aligns with the company's environmental sustainability targets and identifies the most desirable scenarios. The environmental sustainability expert could also assesses these results, comparing the differences between expected scenarios. This dual perspective provides actionable insights for both designers and environmental sustainability experts. The tool emphasizes future environmental benefits and impacts' uncertainties, enabling the environmental sustainability expert to guide the company toward the most favorable scenario.

An illustrative example of the potential applications of this tool can be observed in **Figure 21** and

Figure *22* This illustration demonstrates the distinct roles of environmental sustainability experts and design experts, who operate within distinct workstreams. Furthermore, a comprehensive overview of the various scenarios and potential alternatives is provided. Additionally, access to databases and further modeling details is available. A user-friendly and straightforward interface, such as this, enables the user to effectively manage data, results, and the overall structure of the too.

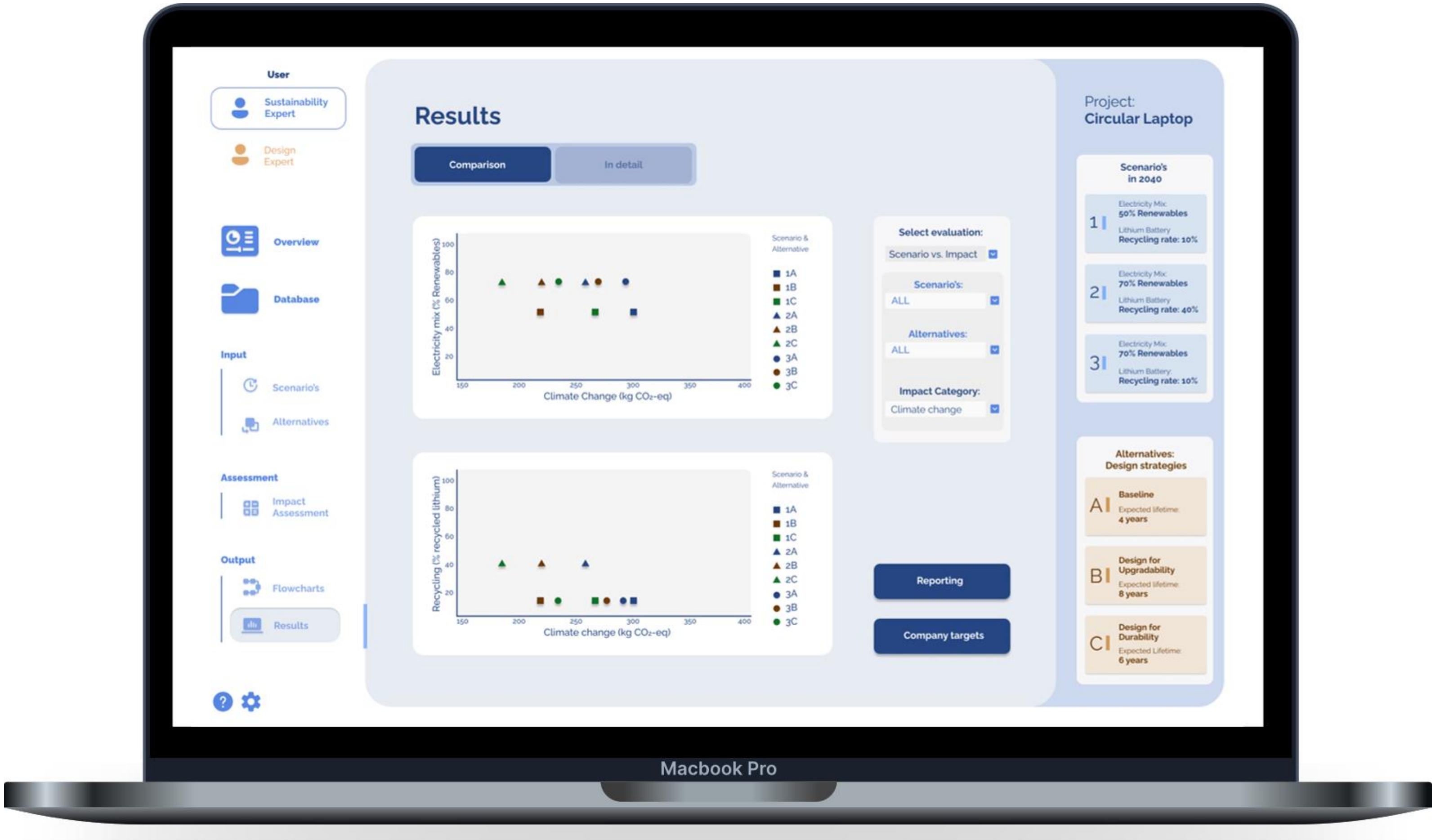


Figure 21. *Example of tool interface for the sustainability expert*

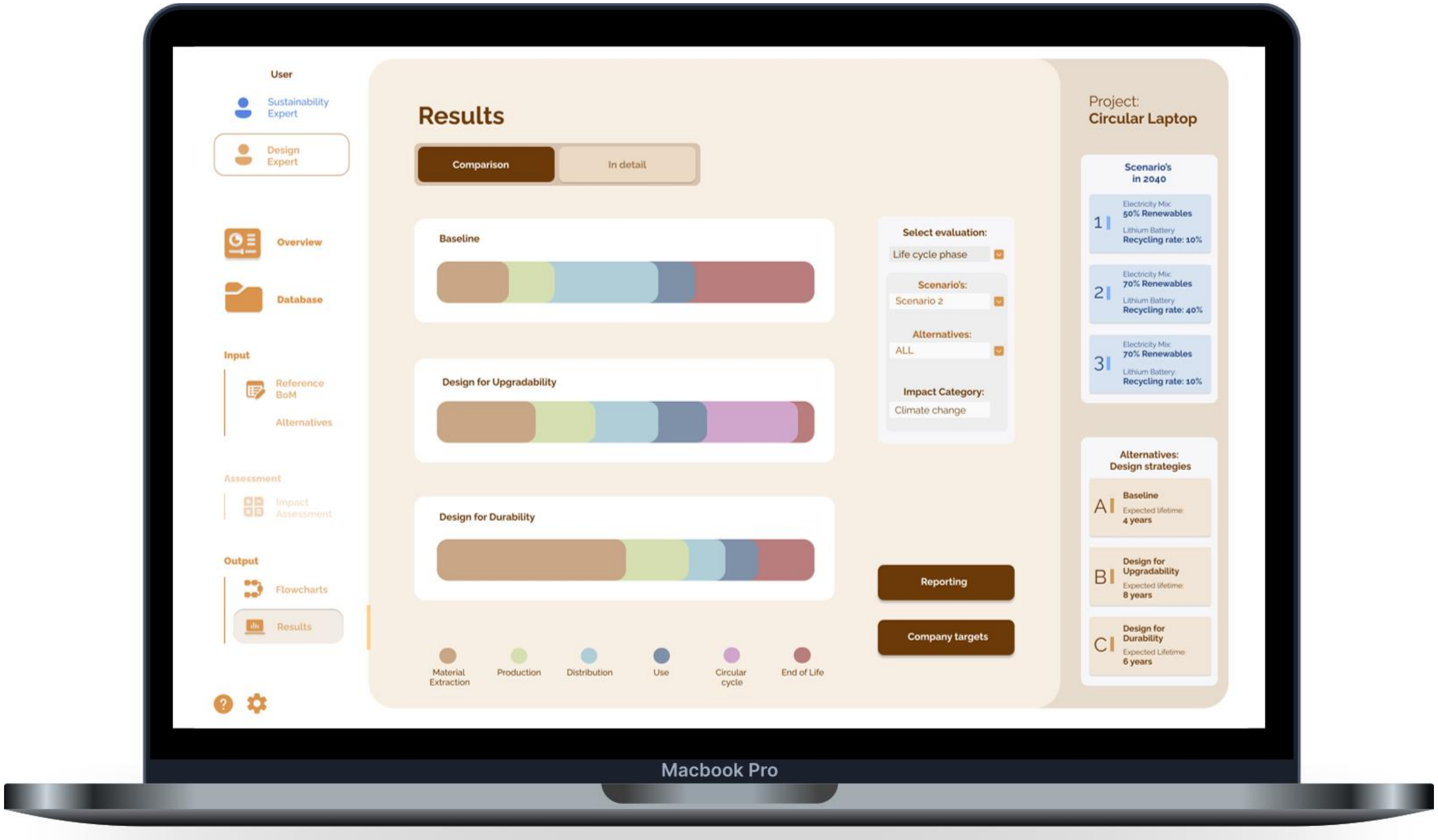


Figure 22. *Example of the tool interface for design exper*

6.

DISCUSSION

This chapter presents the main findings and their limitations. It focuses on the quality and relevance of the study. First, the findings are discussed. Second, the qualities of these findings are analyzed through an examination of the overall research quality. Third, the limitations of the research are argued. Finally, the overall relevance of the study is argued.

The objective of this study was to research the possibilities of effective LCA implementation in the designer’s workflow. The research investigated the potential for avoiding the circularity rebound by improving environmental sustainability assessment tools to encompass the various dimensions of circularity strategies. Additionally, the research aimed to enhance the integration of environmental sustainability assessment into the design process by establishing criteria for tool development utilized in the early stages of design. This was addressed by the following primary research question: *“How can Life Cycle Assessment be integrated into early-stage decision-making processes for the implementation of circular design strategies?”*

To gain deeper insights, the study formulated five sub-RQs. These questions were explored through extensive semi-systematic literature reviews, grey literature analysis, desk research, and semi-structured interviews. The research also involved understanding the designer's workflow, usability testing of simplified LCA tools, and an examination of environmental sustainability assessment methods specific to circular design strategies. These results were assembled in a framework for a new tool development, aimed at enhancing product evaluation and guiding circular design strategies during early design phases.

6.1. THE MAIN FINDINGS AND THEIR IMPLICATIONS

The principal outcome of the research is the identification and development of a program of requirements for an original environmental sustainability assessment tool that effectively integrates LCA into the conceptual design phase. In addition, the proposed tool implements different elements to facilitate better environmental evaluation of circular design strategies. These requirements are designed to address the practical challenges of complexity and usability in existing LCA methods and tools, ensuring that the new tool is user-friendly, actionable, and aligned with business goals while providing accurate and comprehensive environmental sustainability assessments. The proposed tool incorporates several key elements, including intuitive interfaces, modeling of circular strategies, transparent data, flexibility for company-specific data, and the incorporation of ex-ante LCA elements to support long-term strategic planning.

Integrating LCA into the Designers Workflow

The research findings indicate a notable disconnect between the workflow of designers and the low utilization of environmental sustainability assessment tools, particularly during the conceptualization phase. Designers are inclined to rely on intuitive and efficient decision-making processes, drawing extensively from their prior experiences. This finding suggests that the existing analytical LCA tools, which are frequently complex and time-consuming, may not be optimally suited for utilization in the initial stages of design. Consequently, there is a clear necessity to develop LCA tools that are more coherent with the intuitive and expeditious nature of the design process.

The proposed improved alignment of the LCA tool with designers' cognitive processes could significantly enhance the integration of environmental considerations into the design process. By creating tools that are easier to use and more compatible with designers' workflows, there is potential to increase the adoption and effective use of these tools. This would enable designers to make informed environmental decisions without compromising their creativity and efficiency during the ideation phase.

The findings indicate that developers of LCA tools for product design should prioritize the creation of user-friendly interfaces and functionalities that facilitate rapid and intuitive use. Tools that offer streamlined yet comprehensive environmental sustainability assessments and integrate seamlessly into existing design workflows may experience higher rates of adoption, as designers prefer simplified LCA tools. Features such as pre-filled templates, scenario-based evaluations, and real-time feedback could prove particularly beneficial. This aligns with the program of requirements outlined in the thesis, which emphasizes usability and alignment with designers' cognitive processes.

The Early-Stage Design Phase and LCA

The analysis of existing tools reveals a significant trade-off between ease of use and the depth of analysis. Tools with high complexity, such as OpenLCA and SimaPro, offer detailed analyses but are often impractical for rapid, preliminary assessments due to their complexity and the expertise required. In contrast, simplified tools like Sustainable Minds and Ecolizer streamline the process, rendering them more accessible; however, this is often at the expense of data quality and transparency. This trade-off highlights the necessity for a balance between simplicity and accuracy, ensuring that any reduction in complexity does not result in a compromise to the quality and reliability of the results. Various studies have been conducted to acknowledge this balance (e.g., Bonnet et al., 2014; Chen & Huang, 2019; Payen et al., 2018).

To address this challenge, the proposed tool is designed with two distinct user interfaces, one for users with expertise in environmental sustainability and another for those with design knowledge. This dual-interface approach enables the tool to retain its analytical depth while remaining intuitive for both types of users. To illustrate, the sustainability expert establishes the tool by selecting scenarios and defining goals and scope, while the designer is required for the data input. The proposed tool should feature a minimalist, aesthetically pleasing interface with straightforward navigation and visual feedback mechanisms to guide users through the assessment process. This design reduces the cognitive load on the user and allows designers to make intuitive decisions.

The dual-interface approach enhances the collaborations between environmental experts and designers. As found in the current challenges, designers do not know when exactly to incorporate expert knowledge on environmental sustainability into the design process. By establishing a close relationship between the designer and the environmental sustainability expert from the start of the project, the designer can be better informed throughout the design process, eventually leading to more comprehensive and informed design decisions. Furthermore, this approach allows designers to gain familiarity with the field of LCA, thereby enhancing their understanding and expertise in this domain over time. The progressive enhancement of designers' environmental sustainability assessment capabilities and understanding would eventually lead to better-informed decisions during intuitive (System 1) reasoning.

The objective of the proposed tool is to facilitate the process of making informed design decisions rapidly by providing actionable insights and clear workflows. By translating complex LCA terminology into familiar design concepts, the tool reduces the learning curve and enables designers to utilize it with minimal training. This is consistent with the principles of System 1 thinking, which emphasizes the importance of intuitive and rapid decision support. Vallet et al. (2013) discovered that when designers possess greater familiarity with a tool, they tend to rely on their intuition rather than a systematic approach. Similarly, Telenko & Wood (2016) found that while self-reported expertise exhibited a slight reduction in environmental sustainability ratings, no significant correlation was identified.

The proposed tool enables designers to consider not only the immediate environmental impacts of their design choices but also the long-term implications. A principal outcome of this investigation is that the integration of ex-ante LCA into the design process facilitates the implementation of the LCA framework in the initial phases of the design process. By addressing uncertainties in data using estimates and proxies of reference products, an early-stage design can be more readily and efficiently modelled. The ex-ante approach enables the use of LCA as a tool for informing decisions, rather than for the analytical evaluation of decisions. Given the inherent uncertainties associated with data, the results of an ex-ante LCA are better understood as a form of guidance rather than as definitive outcomes. Conducting the ex-ante LCA can be seen as experiments, and the results provide valuable guidance for the early-stage design process, offering direction in often large problem solution spaces. Consequently, ex-ante LCA resembles parts of a design process when viewed through the lens of the five generic elements of a design process (van Dooren et al., 2018).

Moreover, an interdisciplinary team is necessary to inform the ex-ante LCA inventory and scenarios. Similarly, an interdisciplinary design team is typical in the design process to fully understand the problem and provide feasible solutions. The value of ex-ante during the design process is also recognized by research (Villares et al., 2017). This thesis illustrates how it could be implemented in an LCA tool designed specifically for the design context.

Circular Design and Environmental Sustainability Assessment

Whereas the ex-ante approach is beneficial during the initial stages of the design process, the findings further indicate that it enhances the capability of the tools to address circular design strategies. The ex-ante approach provides the design team with a long-term perspective, thereby facilitating strategic planning. These aspects facilitate the implementation of circular design practices, as circularity necessitates the formulation of long-term plans and the anticipation of future events and requirements. This guarantees that environmental sustainability assessments are not only relevant in the present but also in context and aligned with long-term environmental sustainability developments.

The potential for ex-ante LCA to inform early-stage circular product development is supported by the findings of Buyle et al. (2019), who emphasize the value of expanding the current scope of ex-ante LCA to encompass the assessment of alternative circular business models and the related technological developments. Moreover, the research of Grenz et al. (2023) recognizes the value of ex-ante LCA as a suitable approach for future product development and strategy development. The research indicates that the primary advantage of this LCA approach is its capacity to generate a multitude of coherent future scenarios, evaluate their impact on the product's environmental impact, and conclude future product development strategies.

These findings imply that integrating ex-ante LCA into design tools can markedly enhance the capacity and motivation of design teams to plan for long-term environmental sustainability. By providing a strategic framework that accounts for future scenarios, designers can develop products that are better aligned with the principles of the circular economy, which require foresight and adaptability to future requirements and conditions.

Moreover, the findings suggest that an effective environmental sustainability assessment for circular strategies requires a hybrid approach that integrates both quantitative and qualitative assessments. This is of particular importance when evaluating the non-quantifiable environmental implications of design choices. The predominant focus of traditional LCA tools is on quantitative metrics, including carbon footprint, energy consumption, and resource depletion. However, these metrics are insufficient for capturing the broader implications of circular design strategies.

The tool proposed in this study integrates ex-ante LCA methods with additional qualitative aspects, thereby providing a more comprehensive evaluation framework. The ex-ante LCA approach, which involves assessing potential environmental impacts before the full-scale implementation of a product or process, is enhanced through the incorporation of qualitative assessment and guidance on key circular principles, including ease of disassembly, design for emotional durability, and stakeholder engagement. In addition to this qualitative assessment, designers are provided with guidance on the various methods of modeling circular strategies. This guidance calls for additional data details per selected circular strategy, thereby requiring the design professional to consider a range of implications when designing for circularity and environmental sustainability.

These findings have implications for the evolution of environmental sustainability assessment tools, which must extend beyond traditional LCA metrics to incorporate qualitative factors. This evolution is necessary to capture the full spectrum of environmental impacts associated with circular design strategies. By integrating qualitative assessments, designers can better understand and address non-quantifiable aspects of environmental sustainability, such as product longevity and user engagement, which are crucial for achieving circularity. Furthermore, the integration of qualitative aspects into proposed tools underscores the importance of interdisciplinary collaboration. Achieving a comprehensive environmental sustainability assessment will necessitate input from various stakeholders, including sustainability experts, material scientists, and user experience researchers.

6.2. LIMITATIONS OF THE RESEARCH

While this research offers valuable insights into the integration of environmental sustainability assessments for circular strategies, several limitations must be acknowledged.

Generalizability

Firstly, the generalizability of the study is constrained by the limited number of interviews conducted, which focused exclusively on companies within the electronic consumer product sector. While the insights gained are significant within this specific context, they may not fully represent the diversity of challenges and opportunities encountered across other industries. This limitation indicates that the findings may not be directly applicable to sectors with other characteristics, operational processes, or regulatory environments.

Research Bias

Secondly, the research was conducted by a single researcher, which introduces the potential for bias. Despite efforts to mitigate this risk, including the incorporation of expert input throughout the research process and the evaluation of usability findings with design students to integrate a broader perspective, there remains a risk that the individual researcher's perspectives and assumptions could influence the outcomes. It would be beneficial for future studies to adopt a multi-researcher approach or employ triangulation methods to further mitigate the potential for bias and enhance the robustness of the findings.

Methodological Limitations

The exclusive reliance on qualitative methods represents a notable limitation from a methodological standpoint. These methods were required due to practical constraints related to scope, time, and resources. Although qualitative approaches offer valuable insights that are context-specific, the lack of quantitative or semi-quantitative methods, such as surveys, limits the breadth and depth of empirical evidence. The incorporation of quantitative data in future research could facilitate a more comprehensive understanding of the phenomena under investigation and validate the qualitative findings.

Additionally, the literature review was constrained by narrowly focused search terms related to product design, which may have resulted in the oversight of relevant methods and tools applicable to broader aspects of circularity. Moreover, the significant reliance on secondary data from academic literature may introduce potential limitations, as the quality and reliability of such data can vary, potentially impacting the accuracy and validity of the results. It would be beneficial for future reviews to consider a broader range of search terms and primary data sources to ensure a more comprehensive overview of existing knowledge.

The research employed a range of methods, including literature reviews, reviews of educational resources, desk research, and assessments of grey literature. Each of these approaches has inherent limitations, particularly concerning replicability. The current, unstable, and expansive landscape of environmental sustainability assessment tools means that the findings of this study may differ if replicated in the future. Furthermore, the extensive existing grey literature on LCA tools indicates that some relevant tools may have been inadvertently omitted from the final list. It would be beneficial for future research to aim for a more exhaustive review and to consider the dynamic nature of the field.

A further methodological limitation is the synthesis of challenges identified in both the literature review and empirical data. This synthesis may result in oversimplification and overgeneralization. The program of requirements was designed to generalize the needs of design teams and industries, but this approach may not fully capture the specific needs of individual users.

Tool Development

Furthermore, the current research is constrained in its capacity to portray how the proposed tool will be modeled. Although the study addresses complex LCA modeling aspects such as multifunctionality, cut-offs, and recycling loops, it does not provide solutions, as no standardized method has been introduced. These aspects are significant for correctly modeling multiple-use cycles, and their incorporation into the proposed tool is crucial. Subsequent research phases should address these modeling challenges, thereby facilitating a more comprehensive understanding of the concepts among designers and ensuring the accuracy of the results.

Furthermore, the tool's flexibility and reliance on proxy data or clustered material data introduce the potential for subjectivity, which may affect the accuracy and consistency of environmental sustainability assessments. The ex-ante LCA approach introduces uncertainties regarding accurate scenario building for a long-term perspective and the reliability of the environmental impact assessments, particularly given the dependence on environmental sustainability experts to model these scenarios. As the tool is further developed, it should be emphasized that its results are intended to provide directional guidance rather than analytical precision. Furthermore, the subjectivity inherent in the tool's focus on specific product and design scenarios limits its broader applicability across diverse industrial contexts.

Furthermore, the development of the tool is constrained by its reliance on external databases, such as ecoinvent, which provide crucial life cycle inventory data. These databases, while comprehensive, are often costly and may not be accessible to all organizations, particularly in SMEs. The financial burden associated with procuring high-quality inventory data can be a significant obstacle, potentially limiting the tool's accessibility and practical utility for a broader range of users. To address this issue, future development efforts should explore strategies for reducing data costs. One potential option for would be to negotiating partnerships or licensing agreements to make these resources more affordable and accessible. Furthermore, the assumption that the tool would rely on scenario databases with adaptable background processes, as proposed by Steubing & de Koning (2021), requires closer examination.

Practical Use of the Tool

Despite the efforts to streamline the tool, certain aspects of LCA still necessitate expert knowledge. The objective is to resolve the complexity of LCA with the simplicity of the tool, which is achieved through the incorporation of features such as a dual interface. Nevertheless, design teams may still require the input of an environmental sustainability expert, which could restrict the tool's standalone utility for those without such expertise. SMEs may encounter difficulties in allocating the resources necessary for implementation. It is essential to ensure that the tool is scalable and can be used effectively across companies of varying sizes. This can be achieved by adapting the features and support provided to meet the diverse organizational needs of different companies. It would be beneficial for future versions of the tool to consider the inclusion of customizable options, which would allow for its adaptation to different contexts.

The implementation of the assessment tool may entail considerable costs, not only for the software itself but also for the requisite infrastructure upgrades, training, and ongoing support. For a considerable number of companies these costs could prove to be a significant barrier to accessibility. This aspect was not a focus in the current research requirements, which may result in practical limitations in tool deployment. Furthermore, the practical usability of the tool is constrained by its reliance on available reference products that serve as proxy data. The quality, completeness, and availability of this reference data can vary significantly and may be highly context-dependent, which can impact the tool's effectiveness and its ability to provide accurate and reliable environmental sustainability assessments.

6.3. FUTURE RESEARCH

In the field of environmental sustainability assessment for circular design strategies, further research is required to advance the current state of knowledge. Additionally, for the tool to be developed further, supplementary research is necessary to fulfill the requirements. This section addresses relevant aspects that apply to further research.

Integration of Circularity and Environmental sustainability assessment

While this research primarily addresses environmental sustainability assessment, there is a growing emphasis on circularity assessment. In the course of examining methods for eco-design in the context of circular strategies, a substantial body of literature on circularity indicators was encountered, which are employed to assess the degree of circularity in products. Although distinct from environmental sustainability assessment methods, these circularity indicators are recommended for integration with environmental sustainability assessments to provide a comprehensive understanding of a product's circularity (e.g., Jerome et al., 2022; Palomero et al., 2024; Saidani et al., 2021). The question of whether these approaches can be aligned is a matter of ongoing debate. Samani (2023) has noted that even if alignment is feasible, the results may not always be consistent. The recent introduction of a standardized framework for circularity measurement by ISO 59020 (2024) guides measuring circularity while considering environmental sustainability. It would be beneficial for future research to investigate how circularity and environmental sustainability assessments can be integrated to provide a comprehensive framework for decision-making in the design process.

Enhancement of Ex-Ante LCA

Samani (2023) identifies ex-ante LCA as a valuable tool for enhancing circularity assessments. Future research is required to investigate how ex-ante LCA can be developed further to provide greater support for circular product design. This could entail investigating methods for integrating ex-ante LCA findings with broader circularity metrics, thereby providing a more comprehensive understanding of product sustainability.

The Assessment of Sustainability

The current research primarily concentrates on the environmental aspect of sustainability through LCA, with minimal assessment of the economic and social dimensions. It would be beneficial for future research to adopt a more integrated approach that considers the complete sustainability impacts of circular strategies and other design choices. Such studies would enhance the assessment by balancing environmental, economic, and social factors, thus supporting more informed decision-making.

Advanced Modeling Techniques

The utilization of advanced modeling techniques, such as artificial intelligence (AI) and machine learning (ML), in LCAs represents an intriguing field of potential future research. The incorporation of AI, ML, and automated processes is becoming an increasingly pertinent area of research. As illustrated by Makersite (2024), tools that employ AI have the potential to streamline data collection and provide real-time monitoring and optimization. Ghoroghi et al. (2022) demonstrate the potential of ML in optimizing LCAs through the generation of process alternatives. Similarly, Spreafico et al. (2024) propose the use of AI for technological forecasting and scenario development. In the context of circular design, Shevchenko et al. (2024) put forth the proposition of employing AI to augment circular design tools with real-time data on repair, reuse, and remanufacturing. It would be beneficial for future research to investigate the potential for incorporating these technologies into LCA tools, to enhance the efficiency of the process and improve the accuracy of the results.

Expansion to Product Portfolios

The present study was limited in scope to the assessment of single products. It would be beneficial for future research to consider expanding the tool's capabilities to monitor and assess entire product portfolios. Gaining insight into the environmental impact of product portfolios would afford companies a more comprehensive understanding of their environmental footprint. This could entail the integration of MFA frameworks for the monitoring of resource flows about a multitude of products. MFA is frequently employed in circularity assessments (Corona et al., 2019), and its integration with LCA is a common approach for expanding the assessment scope (Lindgreen et al., 2020). Barkhausen et al. (2023) recommend enhancing the flexibility of LCA software and developing tools that integrate MFA and LCA for comprehensive environmental and circularity assessments.

Refinement of Tool Requirements

Several current requirements indicate potential focus areas for future research. For example, requirement 4.2 is concerned with the generation of results that can be acted upon. Future studies could investigate which LCA results are most actionable for designers. In a similar study, Hollberg et al. (2021) proposed an optimized dashboard for building LCA for architecture students which included the most actionable results visualizations.

Another requirement, designated as Requirement 5.2.4, pertains to the formulation of the functional unit. Future research could investigate methods to streamline this phase. One approach might be to guide designers with specific questions, such as "What does your product or service provide?" Another would be to offer a range of LCA goals within the tool, each with different scope and functionality inputs. These aspects, while identified as potential improvements, have yet to be implemented in the current requirements. Future research should focus on simplifying and guiding the definition of scope and goals to enhance efficiency while adhering to the standards set forth by the ISO 14040 (2006) & ISO (14044) 2006) standard.

To address Requirement 3.1.3 regarding data availability, future research should investigate strategies for providing up-to-date databases and inventory data. The current landscape of databases is often private and inflexible, with limited data sharing. Research on improving these challenges is ongoing (e.g., Ghose, 2024). Additionally, enhancing scenario datasets to better model background processes remains a challenge, with ongoing issues related to scenario availability, accessibility, guidance, and software capabilities (Steubing & de Koning, 2021).

Practical Evaluation

Finally, to enhance the practical application of the tool, future research should focus on its implementation and validation with practicing designers. A practical study could involve the utilization of the identified requirements as foundational elements for tool development, including the creation of prototypes and the conduction of usability testing with potential users. This approach would facilitate the generation of valuable feedback on the tool's functionality and user experience, thereby enabling the implementation of necessary refinements. Comparative analysis with established tools would assist in validating the tool's performance and ensuring its reliability in assessing circularity and environmental sustainability.

7.

CONCLUSIONS

This research was guided through a set of research questions, with the main research questions being: "How can Life Cycle Assessment be integrated into early-stage decision-making processes for the implementation of circular design strategies?" Additional sub-RQs were developed to structure the research further:

1. How do designers make decisions in the early stages of the design process, and how does this relate to environmental sustainability assessment?
2. What is the current state of research regarding the utilization of environmental sustainability assessment methods in assessing circular design strategies?
3. What environmental sustainability assessment tools, specifically based on LCA, are commonly known and utilized to enable decision-making, and why?
4. What challenges do designers encounter when making early-stage decisions on environmental sustainability in the design process, and how could this be improved?
5. How could an environmental sustainability assessment tool be designed and structured to facilitate designers in early-stage decision-making on the environmental impacts of circular design strategies?

This final chapter will dive into the research questions, providing the main key takeaways and highlighting the contribution to the field of environmental sustainability assessment.

7.1. KEY TAKEAWAYS

The principal objective of this thesis was to examine and suggest methods for incorporating LCA into the conceptual design phase when implementing circular design strategies. This objective addresses the concerns surrounding the circularity rebound, which challenges the assumption that circularity is inherently environmentally beneficial. Furthermore, the primary environmental impacts of a product are determined at the initial stages of the design process, thus necessitating the utilization of environmental sustainability assessment methods that are compatible with these conceptual phases. Several key conclusions can be drawn based on qualitative research into designers' workflows and cognition, the utilization of LCA and other environmental sustainability assessment methods, and the challenges designers face in integrating environmental sustainability assessment into their workflows.

Research Phase 1: Understanding the Designer and their Workflow

The initial section of the research demonstrated the progression of design theory from its creative origins to its current status as a strategic, interdisciplinary practice. The importance of integrating diverse methods and understanding their roles in early-stage design decision-making was highlighted. It was found that during the initial phases of the design process, a high level of uncertainty and ad-hoc decisions are present, based on the designer's intuition. Designers move iteratively through the design process, continuously refining and evaluating their ideas. By exploring dual-system theory, the chapter illustrated the challenge of balancing the fast-paced, intuitive, creative early-stage design process processes with analytical, data-driven assessments. This underscored the necessity for environmental sustainability assessments to be integrated into the iterative and creative processes inherent to the early stages of design.

Research Phase 2: Researching the Current Landscape of Methods and Tools

The second phase of the research focused on grasping the current landscape of environmental assessment methods and tools and their ability to guide the design process.

The first section of this research studied the application of eco-design methods in their ability to evaluate circular design strategies. Several methods were evaluated, including LCA, life cycle planning, STARDUST, and BECE. These latter three eco-design methods were capable of evaluating circularity strategies through a combination of qualitative assessments and LCA. This combination of qualitative assessment, such as ease of disassembly and planning for the behavior of the consumer, the eco-design methods were able to portray a holistic understanding of the environmental implications of the circular design strategies. This finding indicates that although LCA is a comprehensive quantitative assessment method, it is not sufficient to fully capture the qualitative environmental impacts associated with circularity. This illustrates the necessity for supplementary qualitative assessments to comprehensively address the environmental aspects of circular design strategies.

The second section of this phase examined the current utilization of LCA-based tools in design practice. The investigation revealed that, while several LCA-based tools are available, they are not all suitable for the early stages of design decision-making. Tools such as SimaPro and LCA for Experts (GaBi) are widely recognized, but they are complex, time-intensive, and require significant expertise, which makes them less suitable for the initial stages of product development. Simplified LCA tools, which reduce the complexity and data requirements associated with more comprehensive approaches, are more applicable for the rapid assessment of concept designs. However, these simplified tools also have limitations, such as a lack of transparency and an inability to adequately address uncertainties. The research indicates that making use of interdisciplinary design teams within organizations may prove an effective means of overcoming this challenge. Such teams would facilitate a dual interface, comprising one for the designer and one for the environmental sustainability expert. The user with an environmental sustainability focus should be able to navigate the tool with ease, initiating new projects, linking scenarios, and implementing company-specific input. It is recommended that the designer be granted restricted access to projects initiated and prepared by the environmental sustainability expert. In this project, the designer can create and assess various design concepts and circular design strategies.

The third segment of this phase concentrated on the difficulties encountered by designers when integrating environmental sustainability at an early stage of the design process. These challenges include the complexity of life cycle assessment methods, the lack of accessible tools that integrate environmental sustainability assessment with design workflows, and the need to adapt tools to specific company requirements and goals. The research identifies these challenges and suggests practical solutions, thereby enhancing tools to assist designers in making informed decisions with more comprehensive insights into the environmental impacts of their design choices.

Research Phase 3: the Program of Requirements

To address these challenges, the final phase proposes a program of requirements for a new tool. The proposed tool incorporates a dual-interface system, comprising a user interface tailored to the needs of environmental sustainability experts, who can manage project setups and data integration, and a separate interface designed for designers, who can focus on modeling and evaluating design concepts. This design enables the seamless integration of environmental sustainability assessments into the initial stages of the design process, offering a streamlined and user-friendly interface for designers. The interface and workflow of the tool should be designed in a manner that is both familiar and intuitive for designers. Furthermore, the tool incorporates the ex-ante LCA approach, complemented by qualitative assessments for certain circular design strategies. Ex-ante LCA is a predictive LCA approach, which is used to evaluate emerging technologies before they are fully developed. The ex-ante approach enables the tool to provide preliminary results based on uncertain data. Moreover, it incorporates a long-term strategic perspective for evaluating the potential impacts of the products. The ex-ante LCA approach allows for experimenting with different solutions, which provides guidance in a problem-solution space. This closely resembles elements of a design process. Integrating ex-ante LCA into the proposed tool increases the fit of LCA into the designer's workflow.

The tool's multiple requirements are designed to facilitate ways for designers to overcome challenges while using environmental sustainability assessment tools. The interface of the proposed tool aligns with the iterative and creative nature of the early-stage design process. Additional elements are integrated to evaluate the environmental impacts of circular design strategies accordingly. Moreover, the specific visual results that the proposed tool presents are intended to guide decision-making, allowing for faster and more intuitive assessments.

In conclusion, the integration of LCA into the early stages of the decision-making process for circular design strategies necessitates the simplification of the LCA method, thereby facilitating its accessibility to designers. Designers require structured guidance on both environmental sustainability assessment and the selection of circular design strategies. The currently available tools are ill-suited to the workflow and role of designers during the early stages of the design process. The existing LCA tools are frequently too complex, time-consuming, and reliant on expert input, while the simplified LCA tools lack transparent assessments and are limited in terms of impact assessment, data, and assessment possibilities. To address these limitations, this research proposes a program of requirements for a new tool. The primary requirements include the adoption of the ex-ante LCA approach, the facilitation of more informed decision-making by design teams at the outset of the design process, the reduction of the tool's complexity through the involvement of interdisciplinary teams in organizations, the integration of company-specific goals and datasets, and the development of an intuitive interface with familiar terminology for designers.

7.2. RECOMMENDATIONS

In consideration of the findings, several recommendations can be put forth to facilitate the integration of LCA into the initial stages of the decision-making process for circular design strategies.

Firstly, it is recommended that further development of LCA tools specifically designed for use at the early stages of design be pursued, to re-examine the interfaces and core functions of these tools to better align them with the needs of designers during the conceptualization phase. The main elements to focus on is to make use of the interdisciplinary approach within design teams. Furthermore, the terminology, requested input data, and interface of the tool should be more closely aligned with the knowledge of the designer.

Secondly, the current iteration of simplified LCA software is unable to assess circular products through multiple cycles, which presents a significant obstacle to the evaluation of circular designs. It is therefore recommended that LCA tools be enhanced to better model and assess circular design strategies.

Thirdly, the incorporation of the ex-ante LCA approach into LCA tools will facilitate the early-stage assessment of products that are still in the development phase. By incorporating scenario analysis and long-term impact forecasting, these tools can evaluate different future outlooks, select appropriate circular strategies, and integrate these findings into product development.

Fourth, it is recommended that the types of interfaces and features that provide actionable results for designers be explored. The current LCA tools lack guidance on the interpretation of results and the facilitation of decision support. An intuitive design interface is a crucial element in ensuring the ease of use and rapid familiarization of the software by designers.

Fifth, the lack of visual input and overview in current LCA tools impedes designers' comprehension and interpretation of results. Future research should concentrate on the creation of visual interface designs that can effectively convey the LCA modeling process to designers.

Ultimately, it is crucial to foster greater collaboration between academia, industry, governance, and tool developers to ensure that LCA tools are aligned within the latest research and focus on industry needs. Such collaborative initiatives can bridge the gap between academic research and practical application, ultimately leading to more robust and user-centric LCA tools.

By implementing these recommendations, LCA tools can become more accessible, intuitive, and effective for designers, thereby supporting the integration of sustainability considerations into early-stage design processes.

7.3. CONTRIBUTIONS TO RESEARCH

This research has demonstrated how the LCA method can be adapted to meet the needs of companies and designers, thereby making significant contributions to both the academic and industry. The findings are particularly relevant for industries integrating environmental sustainability into their product development processes. By connecting advanced academic LCA methods with practical tools for designers and organizations, the study addresses a critical need in the field.

One key contribution is identifying significant shortcomings in current LCA tools, especially their inability to support the conceptual design phase and assess the environmental impacts of circular design strategies. These insights are valuable for guiding future tool development and methodological improvements, ensuring new tools are better suited to the early design stages where most environmental impacts are determined.

The research contributes to the interdisciplinary dialogue between environmental science and design, fostering a nuanced understanding of how environmental sustainability can be effectively incorporated into the design process. By examining designers' workflows, behavior, and roles, the research links the dual-process theory to the challenges designers face with LCA, highlighting the misalignment between current LCA tools and designers' workflows.

The study identifies specific requirements for an LCA-based tool tailored to designers' needs, laying the foundation for developing more effective and user-friendly environmental sustainability assessment tools. This includes recommendations for designing user-friendly interfaces, incorporating actionable results, intuitive design, and visual input to enhance understanding and facilitate decision support.

Furthermore, the research explores integrating the ex-ante LCA method into an proposed tool for product design. The ex-ante approach allows for the preliminary assessment of products not yet fully developed through scenario analysis and long-term impact forecasting. This advancement enables designers to anticipate future scenarios, model data uncertainties, select suitable circular strategies, and use the results as guidance in early-stage decision-making.

In conclusion, this research provides a comprehensive program of requirements for an LCA tool that meets the needs of designers and companies, advancing both theoretical and practical knowledge in environmental sustainability in design.

8.

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