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Enabling the Integration of Sustainable Design Methodological Frameworks and Computational Life Cycle Assessment Tools into Product Development Practice

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ENABLING THE INTEGRATION OF SUSTAINABLE DESIGN METHODOLOGICAL FRAMEWORKS AND COMPUTATIONAL LIFE CYCLE ASSESSMENT TOOLS INTO PRODUCT DEVELOPMENT PRACTICE

A Thesis
Submitted to the Faculty
in partial fulfillment of the requirements for the
degree of

Doctor of Philosophy

in

Engineering Sciences

by TEJASWINI (TEJA) CHATTY

Thayer School of Engineering
Guarini School of Graduate and Advanced Studies
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May/2023

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Abstract

Environmental sustainability has gained critical importance in product development (PD) due to increased regulation, market competition, and consumer awareness, leading companies to set ambitious climate targets . To meet these goals, PD practitioners (engineers and designers) are often left to adapt their practices to reduce the impacts of the products they manufacture. Literature review and interviews with practitioners show that they highly valued using quantitative life cycle assessment (LCA) results to inform decision-making.

LCA is a technique to measure the environmental impacts across various stages of a product life cycle. Existing LCA software tools, however, are designed for dedicated experts to use at the end of PD using detailed product information. This creates the *"ecodesign paradox"*, a tension between opportunity for change in the early-stages of PD and availability of data in later stages to make reliable decisions. Further, my research identified that *novice* users of LCA face additional barriers including: cumbersome user interfaces, unfamiliar terminology, and complicated information visualization. To address these challenges, I co-created a tool called EcoSketch for use during early-stage PD by novice users.

Practitioners, however, also struggle with translating environmental impact information into actionable design decisions. Hence, I researched how to effectively co-create methodological frameworks of sustainable design strategies with industry partners, Synapse Product Development and Stanley Black and Decker, to improve receptivity and adoption. Despite contextual differences, a key commonality was that practitioners at both firms sought "structured" and "data-driven" processes for sustainable design.

Through multiple, extended internships, I also identified important drivers and barriers to sustainable design integration. Overall, my research demonstrates that co-creation improves receptivity, long-term adoption, and produces tangible improvements to sustainable outcomes in practice.

In summary, my research pursues two key pathways to enable sustainable design integration:

1. Developing **human-centered life cycle assessment (LCA) tools** that are easier to use for decision-making during the early stages of PD.

2. Creating **methodological frameworks and a process for effective co-creation** to support the application of appropriate sustainable design strategies in PD practice.

This thesis elaborates on my proposed coupling of robust frameworks with human-centered LCA tools, which I argue together comprise a transformative solution for industry professionals to effectively integrate sustainability considerations in their product development practices.

Acknowledgements

My journey to developing a passion for the planet started young through conversations with my grandfather, Dr. C. N. Rao, a professor of geology and geophysics at IIT Kharagpur. He shared many stories about his field work all across India and Central Norway, and instilled in me a love and care for the planet with all of its beautiful rocks and species. This underlying passion drew me to applying my newly acquired mechanical engineering skills to projects on sustainability during college, and my subsequent decision to study sustainable design and manufacturing at Dartmouth College. This thesis is a tribute to my grandfather, whom I lost to COVID in 2020, making it the darkest period of the PhD program and my life. He lives on in my heart and continues to motivate my passion for the planet and my love of nature.

First, I would like to thank my advisers, Prof. Jeremy Faludi and Prof. Liz Murnane, for believing in me and providing valuable guidance throughout the program. Jeremy was instrumental in helping make the industry connections, while Liz provided valuable input on the human-centered design and development of EcoSketch.

Next, I would like to thank all my industry partners and research participants at Synapse Product Development (Synapse), EarthShift Global (Earthshift) and Stanley Black & Decker Inc. (SBD); especially Will Harrison from Synapse, Lise Laurin and Bryton Moeller from EarthShift, and Dr. Dan Fitzgerald from SBD for their mentorship as well as contributions to my research papers.

Mentors, professors, and supporters at the Thayer School, including Prof. Steve Peterson, Prof. Mark Laser, Prof. Petra Bonfert-Taylor, and Amy Keeler from Career Services, and Prof. Eric Fossum from the PhD Innovation Fellowship, were all instrumental in my growth as a student, teaching assistant, researcher, and activist.

Without support from all of the undergraduate and graduate student interns at the DALI Lab and the Empower Lab, none of this work would have been possible. Thank you Alessa, Ana, Andra, Bryton, Catherine, Dev, Grace Qu, Grace Wang, Hana, Julian, Luc, Nina, Pape, Rachel, Ryan, and Samiha.

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Finally, I would like to extend my sincere appreciation to anyone who may have been inadvertently omitted from this list of acknowledgments. Your contributions and support have not gone unnoticed, and I am deeply grateful for your involvement in my journey.

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List of Acronyms

Product Development	PD
Sustainable Design Methods and Tools	SDMTs
Stanley Black and Decker Inc.	SBD
Life Cycle Assessment	LCA
Simplified Life Cycle Assessment	SLCA
Human Computer Interaction	HCI
Sustainable Human Computer Interaction	SHCI
Environmental, Social, and Good Governance Metrics	ESG
Corporate Social Responsibility	CSR
Life Cycle Inventory	LCI
Bill of Materials	BOM
Computer-Aided Design	CAD
System Usability Scale	SUS
Stochastic Multi-Attribute Analysis	SMAA
Research Question	RQ
New Product Introduction	NPI
Project Managers	PM
Stanley Engineered Fastening	SEF
Black & Decker	BD
Extended Producer Responsibility	EPR
All-Terrain Vehicles	ATV

Chapter 1. Introduction

Public, private, and academic discourse continues to grow around issues of environmental sustainability and what society can do to mitigate climate change. As frequent extreme climate events threaten our energy systems [1], food systems [2], and biodiversity [3], industries are setting ambitious climate targets to decarbonize their operations, such as, achieving net zero emissions. In companies that engage in hardware product development (PD), these climate targets trickle down into PD practice in the form of decisions related to the product's materials, manufacturing processes, energy efficiency, circular end-of-life models, and other sustainable design strategies that can help reduce environmental impacts. Professional engineers and designers (collectively referred to hereafter as "practitioners") who engage in PD are often responsible for figuring out how to adapt their practice to incorporate these sustainability considerations effectively to meet climate targets. While there have been strides in sustainability education at engineering schools [4], most mid-career practitioners have to learn on the job. My prior research, detailed in Chapter 2, shows that practitioners initially perceive sustainable design integration negatively, as time-consuming, expensive, and as a hindrance to creativity. Exposing them to the environmental and economic benefits of sustainable design through workshops on a variety of existing sustainable design methods and tools (SDMTs) created a positive shift in perceptions [5]. Additionally, research undertaken as part of this thesis shows how co-creating [6] new sustainable design processes with users, while paying close attention to context-specific drivers and barriers to adoption, enhances receptivity and long-term retention [7]–[9].

The case studies, detailed in chapters 4 and 5, conducted at Synapse Product Development Inc. (Synapse), and Stanley Black & Decker Inc. (SBD), show that despite contextual differences, practitioners at both firms sought "systematic", "data-driven" processes to systematically incorporate sustainable design principles into their PD practice. Enabling data-driven decisions, however, requires quantifying environmental impacts to identify hotspots and select appropriate sustainable design strategies to address these hotspots. In PD practice, this is typically achieved by modeling the product's material and energy flows in great detail using a method called life cycle assessment (LCA). LCA is a quantitative technique to evaluate the environmental impacts of a product throughout its life cycle, encompassing extraction and processing of raw materials, manufacturing, distribution, use, and final disposal [10], [11]. Some argue that LCA is the most powerful method to evaluate environmental performance [12]. Further, there is a growing consensus on the need to perform LCAs early-on to inform decision-making [13].

The early stages of PD are, however, rife with uncertainties, as critical decisions (e.g., about choice of materials, manufacturing processes, and product architecture) are yet to be made. Ironically, these early stages hold the greatest potential for reducing environmental impacts owing to flexibility and low cost of making changes. This is dubbed the "ecodesign paradox" [10], illustrated in Fig 1, and poses a critical challenge to effectively integrating sustainability into PD practice. This is further exacerbated by the fact that existing industry-standard LCA software tools do not cater to the sensemaking needs of practitioners who are novice users of LCA. Research detailed in

Chapter 2 identifies several usability challenges posed by existing LCA tools, including but not limited to: 1) cumbersome user interfaces, 2) unfamiliar terminology known only to LCA specialists, 3) complicated information visualizations for the results of the assessment [14]. My research seeks to address the ecodesign paradox through two key pathways: a) creating methodological frameworks to support the application of appropriate sustainable design strategies in PD practice. b) developing human-centered life cycle assessment (LCA) tools that are designed to support decision-making during the early stages of PD.

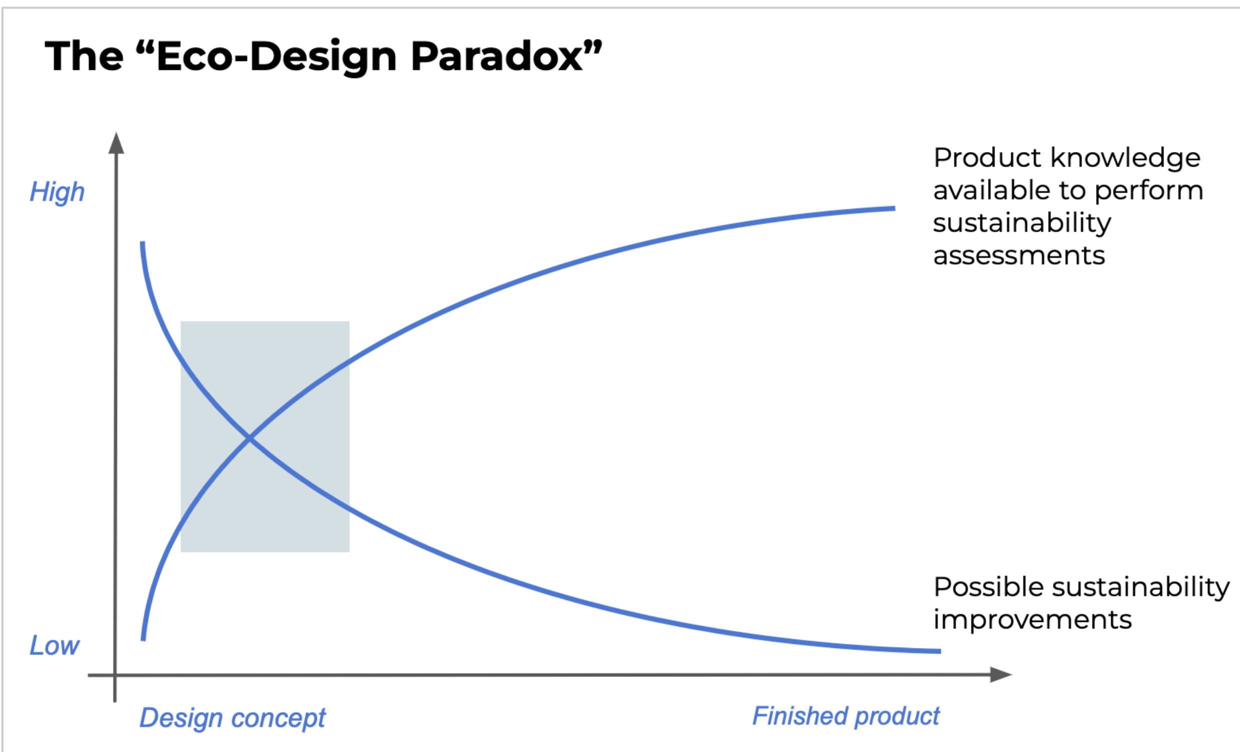

Figure 1: Graphical illustration of the "ecodesign paradox" adapted from [10], showing how the early-stages of PD suffer from limited product knowledge but hold the greatest potential for improvement.

In subsequent sections of this chapter, I discuss relevant prior research in sustainable product development practice, corporate sustainability, and the design and development of LCA tools to support sustainable design. Elaborating on insights in literature that my research is building upon, I also identify critical gaps that my work addresses thereby outlining the intellectual merit to this thesis. Finally, I conclude this chapter with the overarching research questions that my work seeks to answer.

1.1 Sustainable Product Development Landscape

According to [15], product innovation is seen as an important strategy to address the systemic risks that climate change poses to companies and governments, making sustainability an important consideration in PD practice. Academic researchers and practitioners alike have therefore developed numerous SDMTs in recent decades. Early forms of sustainable design [16], [17], focused primarily on redesigning individual qualities of products such as improving recyclability. Recent efforts, however, have expanded in scope to look at the various life cycle stages of the product, and further to include the whole system that the product operates in [18].

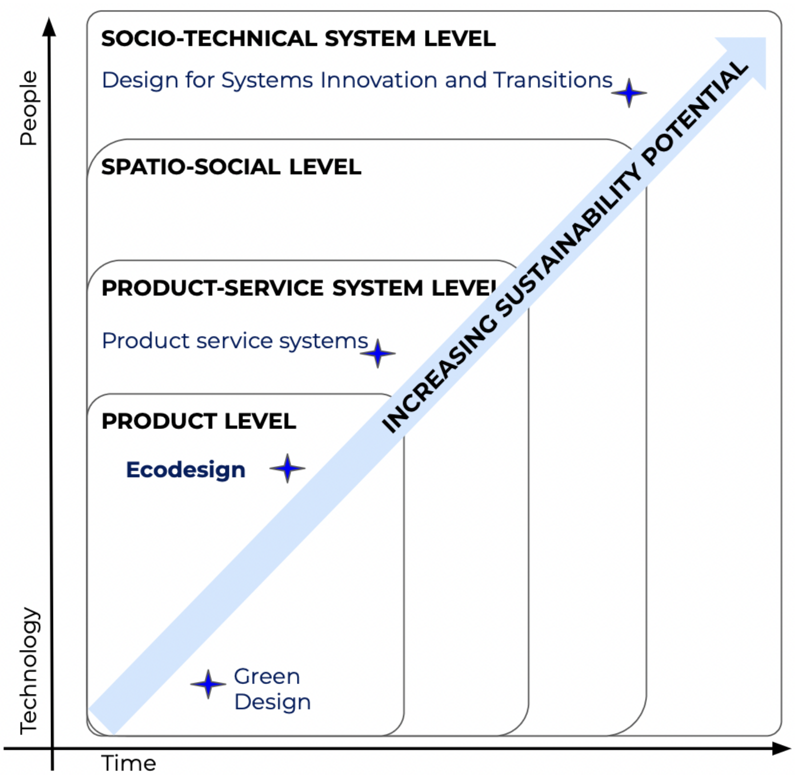

Figure 2: The evolution of sustainable product development practice, adapted from [18].

Empirical studies show that practitioners often do not utilize SDMTs as whole methods, but rather mix and match parts of different methods opportunistically [19], just as they do with traditional engineering design methods [20], [21]. The vast variety of SDMTs in literature are often classified by PD stage [22], on a spectrum of qualitative checklists to quantitative impact assessment tools [23], and by whether they address environmental, social, or economic aspects [24]. Furthermore, terms like "design for sustainability", "ecodesign", "design for environment" etc., are often used interchangeably to refer to various forms of sustainable product development. Similarly, there is no universal consensus around terminology for sustainable product development practices in industry, but this paper uses the following definitions from [22]:

- An "activity" is something that practitioners physically do (e.g., calculate) in PD
- A "mindset" is something that practitioners mentally consider (e.g., a paradigm)
- A "tool" is an artifact (physical or digital) used to perform an activity and/or spur thought along a certain mindset;
- A "method" is a prescriptive, ordered set of activities and mindsets;
- A "strategy" is a collective term used to describe either activities or mindsets;
- A "practice" refers to any and all sustainable design methods, activities, mindsets, tools or combinations thereof applied;
- A "practitioner" primarily refers to professional designers and engineers, but also other stakeholders such as project managers engaged in decision-making and execution as part of the PD process.

Since most practitioners lack training in sustainable design [4], [25], they struggle with both quantifying environmental impacts through LCA as well as identifying the appropriate strategies to address those impacts. The existence of a massive variety of SDMTs makes these choices harder, along with the fact that the early-stages of PD are rife with uncertainties. The next section discusses research on the design, development, and application of LCA tools in PD practice, as well as identifies critical gaps that the tool we developed seeks to address.

1.2 Life Cycle Assessment Tool Design, Development, and Use for PD

LCAs are typically performed using software tools that let users input product data, choice of inventory databases, and impact assessment methodologies in order to compute environmental impacts [26]. Industry-standard LCA tools that enable users to perform ISO-certified [27], and third-party verified environmental product declarations often do not cater to the needs of novices such as the practitioners engaged in PD [14]. Per the ISO 14040 & 14044 [27] definition, LCA examines the environmental impacts throughout a product's life cycle via four distinct steps (illustrated in Fig 3):

1. *Goal and Scope Definition* establishes the goals of the assessment, the functional unit which is the smallest common unit across processes, system boundaries, and data granularity.

2. *Life Cycle Inventory* quantifies the energy requirements, raw material needs, emissions, and waste generated at each stage of a product's life cycle.

3. *Life Cycle Impact* Assessment evaluates the magnitude and significance of a product's potential environmental impacts.

4. *Interpretation of Results* identifies hotspots based on the impact assessment, evaluates completeness, sensitivity, and consistency, along with documenting conclusions, limitations, and recommendations for improvement.

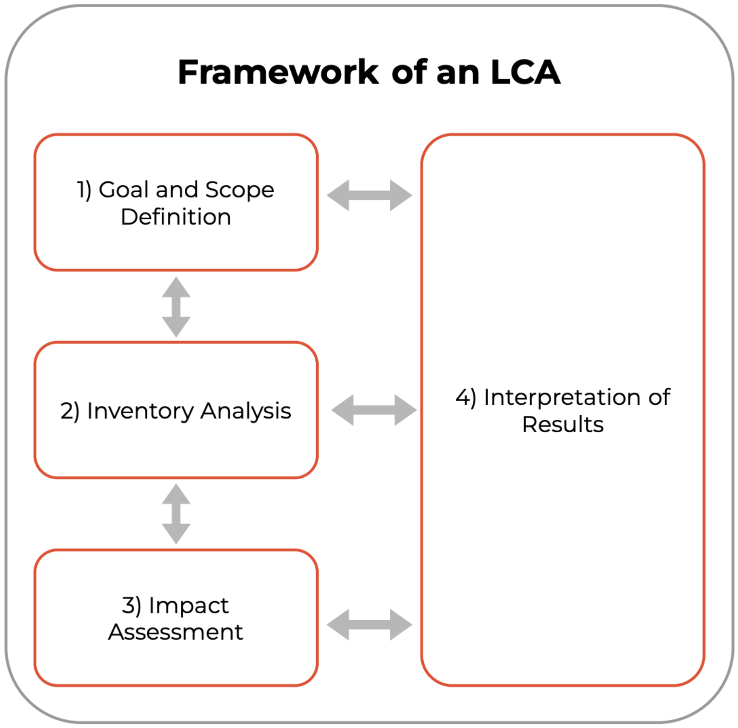

Figure 3: The framework of an LCA describes the four steps in the process that are performed iteratively to quantify environmental impacts: 1) Goal and Scope Definition, 2) Life Cycle Inventory, 3) Life Cycle Impact Assessment, and 4) Interpretation of Results, adapted from [27].

The Life Cycle Inventory step generally takes the most time, as it involves conducting extensive research to precisely identify and quantify all the input and output energy and material flows in the system, often requiring collecting data from a variety of stakeholders and sources, while ensuring it meets the data quality standards required for reporting, regulatory compliance, and making accurate marketing claims. This step is typically performed at the end of the PD process when the data is available with relatively low uncertainty, once the architecture and manufacturing decisions are locked in [28]. However, it is important to perform LCA early-on in PD where the potential for improvement is greater [29], as shown in Fig 4.

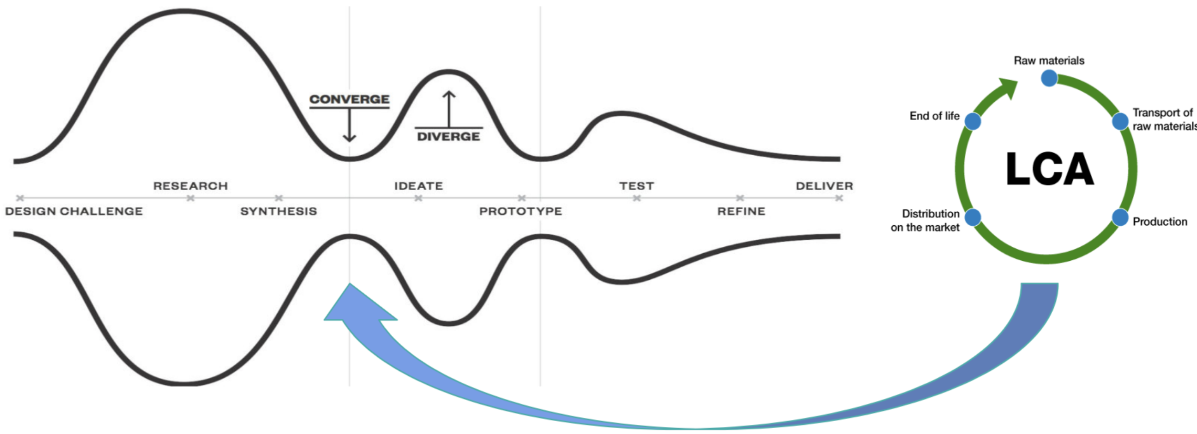

Figure 4: Illustration of how LCA is typically used at the end of the PD process, but my research seeks to make it accessible and applicable early-on. The PD process is represented as a series of diverging and converging steps, adapted from IDEO [30].

As part of my research, detailed in Chapter 2, I evaluated existing LCA tools ranging from industry-standard tools used for peer-reviewed LCA studies to simplified LCA (SLCA) tools that are intended for internal decision-making. The latter hasten the assessment process and help ease adoption of LCA in fast-paced contexts such as new product development [31], and are hence highly relevant to this research. Specifically, SLCA tools are intended to enable quick improvement of the environmental impacts of products and achieve a higher level of sustainable innovation by being applied earlier on in PD. Whereas it would be infeasible to perform a standard LCA in this context as it would be expensive, time-consuming, and require detailed input data that is often unavailable at this stage [32], [33].

Literature review and my evaluation of existing LCA tools with practitioners shows that most tools (both industry-standard and SLCA) are not designed through user-centric approaches to make them effective for novice users. Designing human-centered LCA tools that cater to the needs of the practitioners and their context requires applying well-established techniques and principles from human-computer interaction research (HCI). The next section explores literature that applies HCI research to develop tools for sustainability, highlighting the importance of bridging these disciplines to build better LCA tools for industry use.

1.3 Intersection of Sustainability and HCI

Within the HCI research community, Sustainable HCI (SHCI) research has increasingly grown in priority since the first publication on “sustainable interaction design” 15 years ago. SHCI refers to research focused on limiting the environmental impacts of technology or using HCI as a means to promote environmentally friendly outcomes. Upon reviewing literature at HCI venues since the first article appeared, I found that most papers in the SHCI space broadly fall into the following categories: personal eco-feedback technology, development of energy efficient software systems, design theory and frameworks, reviews and critiques, and digital tools for sustainable design.

Papers on personal eco-feedback technology focus on persuading individuals or small groups to engage in sustainable behaviors that lead to a reduction in their environmental impacts in everyday life [34]. This work often intersects HCI with the field of environmental psychology. For example, [35] looked at the receptivity of personas with diverse age ranges to eco-feedback formats such as electricity bills. Other work [36], [37] designs applications that inform users about their electricity consumption through gamification to enhance persuasion.

Regarding SHCI and sustainable software development, research has largely focused on reducing the environmental impacts of software applications and systems — for instance by recommending strategies for low-power web applications [38], technical infrastructure

[37], and digital services [39]. Design frameworks have also been offered to help technologists consider strategies for reducing the energy and space consumption requirements of digital devices [40]. This emerging field of sustainable software engineering is important and exciting; however, it does not address the development of tools to support sustainable design practices. In fact, there has only been one published paper [41] at a major HCI conference (CHI) focusing on the development of a digital artifact or system for the sustainability needs of industry design practitioners. Reviews of the SHCI literature acknowledge that it is extremely complicated to develop life cycle analysis tools for industry applications [42], which explains why such work is rare so far.

Overall, the SHCI community has mostly focused on either promoting sustainability on the individual-level or at the policy-level. With this thesis, I emphasize the need for attention on another layer of human activity: industries. I hope that my published research and PhD thesis will help the HCI community take a meaningful step towards developing better digital sustainability tools for industrial PD practice.

1.4 Corporate Sustainability Practices

In recent years, there has been a spurt in the development of novel SLCA tools, carbon calculators and widgets developed for industry practitioners by industry. Some examples include, the Microsoft Sustainability Calculator [43], the Idemat app [44], the Sustainable Apparel Coalition's Higg Product Module [45], and the BEAM estimator [46] which is currently in beta testing. This is a testament to the growing need for digital sustainability tools at organizations. This is driven by several factors, including pressure from investors to report and make progress on environmental, social, and good governance metrics (ESG) leading thousands of publicly-listed companies to set ESG strategies [47]. ESG indicators are defined as follows: (i) *environmental performance indicators* refer to practices such as formulating environmental policies, implementing pollution controls, etc.; (ii) *social performance indicators* refer to practices such as the formulation of health and safety policies, and (iii) *governance performance indicators* include metrics such as diversity of board members [48].

The number of investors committed to integrating ESG issues into investment decisions has grown exponentially [49], with research linking ESG disclosures to lower capital constraints [50], and costs of capital [51]. Investors are demanding information on ESG performance to help assess the climate risk attached to their investments. Mandatory and voluntary reporting of ESG performance, however, does not necessarily translate to improved ESG performance [52].

During my time at SBD, I observed that investor pressure played a big role in the company appointing executive leaders and building a Corporate Social Responsibility (CSR) team that I was part of. The team is responsible for publicly setting ambitious science-based targets on various ESG metrics, and reporting the company's annual progress towards these goals, among other functions. However, there is a critical gap in the translation of these ESG targets into actionable day-to-day tasks that practitioners can perform to contribute to improvements. Ref. [53] suggests that at product manufacturing firms, such as SBD, incorporating sustainability considerations early-on in PD and considering the whole life cycle can reveal opportunities for improved ESG performance.

As part of my research, detailed in Chapters 3 and 4, I co-created frameworks of sustainable design best practices to help practitioners at Synapse and SBD systematically incorporate sustainable design principles into their PD practice. Examples of such frameworks in literature include: the checklist for sustainable automotive product development [54], the material criticality assessment [55], and the sustainability compliance index [53]. These frameworks seek to guide practitioners through the iterative selection and application of appropriate sustainable design strategies based on LCA results and other client priorities. However, they do not involve researchers being fully embedded at the companies to gain deep insight into the organizational context, build relationships, and co-create processes to effectively and efficiently incorporate sustainable design. A systematic review by [56] on ecodesign implementation identifies the organizational context as a critical factor. Ref. [57] highlighted that the "soft side", or the "human side" [58] can make or break ecodesign implementation. Further, a large-scale survey conducted by [59] identified "management" as the biggest challenge to ecodesign implementation, closely followed by "collaboration", "strategy", and finally, "tools". Similarly, [60] and [61] highlighted the importance of shifting organizational culture to successfully achieve a competitive advantage from sustainability. In this thesis, my human-centered approach combines participatory design [62] and co-creation [6] to gain deeper insight into the human side through observation, participation, and interviews, guiding the iterative design of the framework. My research confirms that this approach enhances receptivity, acceptance, and long-term integration [8].

1.5 Overarching Research Challenges

We use the "ecodesign paradox" to scope the focus of this thesis around two key challenges:

1. Practitioners face barriers in quantifying the environmental impacts of their design decisions early-on in the PD process.

2. Practitioners face barriers in translating the environmental impact results generated by LCA tools into actionable design decisions leading to sustainable outcomes.

The next chapter addresses Challenge #1 and discusses the rigorous human-centered design process undertaken to design and develop a novel LCA tool. The remainder of the thesis is organized as follows: Chapter 2 discusses my collaborative effort with the DALI Lab at Dartmouth and EarthShift Global Inc., with input from practitioners, to design and develop a simplified LCA tool tailored to the PD context. Chapters 3 and 4 outline the case studies conducted at Synapse and SBD to co-create and integrate sustainable design processes into their PD practice respectively, along with the methods used for data collection, and results. Chapter 5 summarizes key findings from all the research, expands on the broader impacts of the work, and outlines a roadmap for other practitioners seeking to integrate sustainable design into industry PD practice.

Chapter 2. EcoSketch

To address the gap in human-centered LCA tools tailored to novice users seeking to calculate the impacts of their product concepts in the early stages of the process, I managed a two-year long project to design and develop "EcoSketch". The project followed a rigorous human-centered, iterative process, paying close attention to the needs of practitioners. A systematic user research process unearthed critical deficiencies in the ability of existing tools to cater to the sensemaking needs of designers and engineers. These insights were then used to undertake a highly iterative process following an agile workflow to build EcoSketch. The tool was then evaluated on its usability and workflow efficiency. The timeline and major milestones of this research project are detailed below in Fig 5:

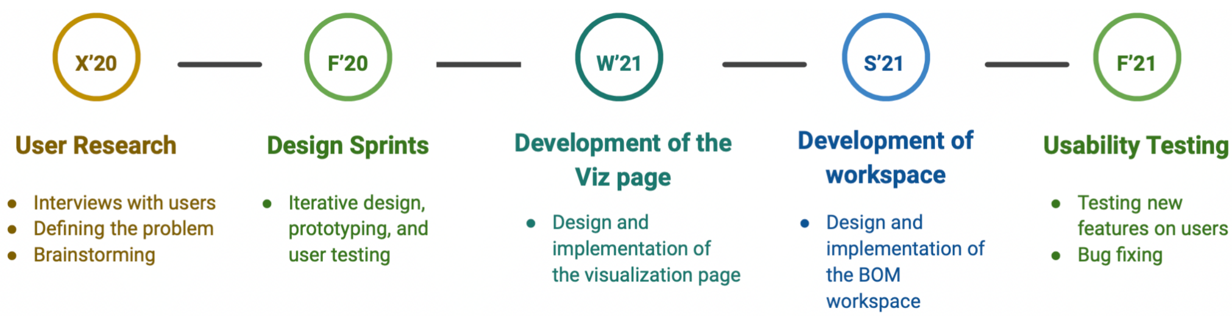

Figure 5: Design and development timeline *(X = Summer, F = Fall, W = Winter, S = Spring)*

2.1 User Research: Evaluating Existing LCA Tools with Users

The motivation to pursue this project came from observations made during my industry internship with Synapse. The sustainable design framework that I co-created with Synapse [8] relied heavily on using simplified LCA (SLCA) tools to perform assessments quickly and iteratively throughout the PD process. During this period, we tested numerous existing LCA tools ranging from industry-standard options like SimaPro and GaBi, to well-known SLCA tools like Sustainable Minds and Ecolizer, to find a good fit for the company.

Practitioners at Synapse learned to use these tools in practice, and rated them on several factors including: learnability [63], ease-of-use [64], and effectiveness of visualizations [65], together with other LCA specific criteria. The choice of metrics is derived from thematic analysis of interviews as well as established usability guidelines [66]. Ultimately, I sought to identify an LCA tool that addresses all the issues identified by the "ecodesign paradox", and is accessible to novice users. First, performing an LCA requires *extensive data* on materials, processes, and energy that may not yet be defined in the early stages. Obtaining this data and building a model is often very *time-consuming*, especially when there is *uncertainty*. Lastly, the whole process from defining scope through impact assessment requires *LCA expertise*.

The following subsections describe the research methods applied to conduct user research, the design guidelines derived from this research, applying these guidelines to design and develop a lightweight LCA tool, and finally performing usability testing.

2.1.1 Methods: Study Context

At Synapse, I worked as a sustainable design intern on a team of four engineers over a period of four months, observing and participating in PD projects to discover how to support the integration of sustainable design and LCA. Participants **P1 - P4** were employees at the firm with varying levels of work experience and exposure to LCA. P1 was in-charge of the sustainable design initiative at the company and volunteered to learn how to use the advanced LCA tools: SimaPro and GaBi. P2 and P3 were mechanical engineers, and both learnt to use Sustainable Minds and Ecolizer, the lighter-weight LCA tools. Finally, P4 primarily worked with EcoSmart. Through discussions, they shared feedback, insights, and taught each other how to use all these tools over the course of the study. Their sustainable design process (Chatty, 2020) involved applying iterative cycles of 1) measuring environmental impacts using LCA, 2) identifying hotspots, and 3) applying relevant design strategies to tackle those hotspots. This research helped explore which existing LCA tools were best suited for use in their fast-paced PD context.

2.1.2 Data Collection

Being embedded at the company allowed me to build a strong rapport with the employees to help gather honest feedback. The main modes of data collection for this study were interviews, think-aloud testing, and surveys.

Interviews: All four participants (P1 - P4) participated in 45-minute-long interviews which covered topics such as: learning curve, visualizations, and reliability. These interviews were conducted after the participants learned how to use various existing LCA tools. Each participant focused on one tool for the interviews and think-aloud testing except P1 who answered questions on both SimaPro and GaBi. P2 and P3 worked on Sustainable Minds and Ecolizer respectively, while P4 used EarthSmart. These tools ranged in complexity from simplified calculators such as Ecolizer to complex industry-standard tools like SimaPro and GaBi. All interviews and think-aloud tests were audio-recorded and transcribed for qualitative analysis. Some examples of questions asked during the interview include:

- How did you learn to use this tool, and how long did it take you to learn?

- Does the format of visualization in this tool support sensemaking? Why?
- Does the format of visualization in this tool support communication? Why?
- How would you rate the reliability of results obtained from this tool? Explain your reasoning for the rating.

Think-aloud Testing: Think-aloud testing is a valuable user research method for collecting qualitative insights from participants on their user experience. Participants think-out-loud as they interact with the interface, voicing their thoughts, areas of confusion, and opinions. My role as the administrator is limited to encouraging them to continue verbalizing if they stop, as per the Boren and Ramsey protocol applied [67].

Each think-aloud test lasted 45 minutes, and was conducted following the interviews. The test involved the participants walking through the various screens and functions of the tool and vocalizing their thoughts, feedback, and questions. Similar to the interviews, P1 used SimaPro and GaBi, P2 used Sustainable Minds, P3 used Ecolizer, and P4 used EarthSmart. At the end of the test, participants were asked to reflect on their interactions and voice any additional feedback they had, including how confident they felt performing LCAs on the tool.

Surveys: The surveys were conducted at the very end of my research study with Synapse by when all participants had gained familiarity with all tools. All four participants responded to the survey, rating all five tools, resulting in a total of 20 survey responses. The survey required all participants to rate all tools on a set of criteria on a Likert Scale of 1 - 5, where 1 was poor, and 5 was excellent. The criteria reflect the themes extracted from the interviews and think-aloud testing. They were further refined based on usability literature and defined as follows:

- *Learnability* relates to the duration and complexity of the initial learning process associated with learning to effectively use a particular tool [63].
- *Ease of use* refers to a tool's usability, which entails the fulfillment of effectiveness, efficiency, and satisfaction during interactions with it [64].
- *Breadth and depth of databases* relates to the choice of inventory databases, including access to specialized databases for the life cycle inventory step of model-making.
- *Reliability of results* is affected by various forms of uncertainty stemming from: a user's lack of experience, inaccuracies in the inventory databases, and a lack of precision in input data.
- *Effectiveness of visualizations* encompasses both aesthetics of the visualizations generated as well as their ability to aid sensemaking and communication [65].

2.1.3 Qualitative Data Analysis: Identifying Themes

Along with a co-author, I performed a thematic analysis to extract insights from the transcripts of the interviews and the think-aloud testing. We ensured inter-coder agreement on both top-level themes and sub-themes over independent and collaborative iterations, using an inductive approach [68]. Any disagreements identified during the inter-coder reliability test were discussed and resolved to achieve 100% agreement. Table 1 outlines these themes.

Table 1: Coding scheme from thematic analysis of qualitative data

Main themes	Sub-theme (Description of the code)
Learning curve	Tool's guidance (e.g., pop-up instructions, video tutorials, expert help)
	Necessity of prior experience (e.g., expertise with LCA concepts or other tools)
	Time and effort it takes to learn
Ease of use (efficiency, effectiveness, satisfaction)	Efficient interaction with pages (slow load time, saving after every input, etc.)
	Minimal number of clicks to perform a task
	Consistency in terminology
	Redundancy in features
	Supporting collaboration
	Aesthetics of the tool
	Familiarity with other tools (Excel, CAD tools)
Breadth & depth of databases	Choice of inventory databases (e.g., ecoinvent)
	Choice of impact assessment methods (e.g., TRACI, ReCiPe scoring, etc.)
	Disposal scenarios (end-of-life)
Uncertainty	Uncertainty from tool complexity and novice confusion (lack of confidence)
	Uncertainty in the database (unknown uncertainties in inventory databases)
	Uncertainty in input information (limited knowledge in early stages of PD)
Visualization	Visualizations that support comparisons
	Visualization format and aesthetic (for e.g., legends, labels and graph colors)
	Representing uncertainty (error bars, blur charts, etc.)
	Communication & interpretation with colleagues (internally)
	Communication with clients (externally)
	Data exporting/visual summaries
Standalone	Using other tools to generate visualizations, write reports, etc.
	Using other LCA tools to validate results

	Using Excel to create a BOM for the product before data input
Workflow	Model setup: setting specs for analysis (functional unit, scope, etc.)
	Model-making process
	Analysis / calculations
	Interpretation of results

2.1.4 Qualitative Data Analysis: Extracting Insights

Learnability and Ease-of-Use

A key observation from my participation in Synapse' workflow was that practitioners were highly constrained on time. Hence, for LCA to be adopted, it would have to be performed rapidly. My interviews identified that a tool's swift *learnability* and efficient *ease of use* were therefore paramount.

About her first modeling experience, P2 said, *"If I really concentrated on it, it could be done in an hour. Because the tool walks you through the process, so you can't really miss anything"*, referring to how the learnability of Sustainable Minds enhanced its usability. In a similar vein, P3 described his experience with Ecolizer, *"I don't think it really took that long. Maybe an hour, I think, to get the base functionality."* P3 pointed out how the learning process was hastened when the interface and icons were similar to familiar tools. For example, the hierarchical model structure of parts, sub-assemblies, and assemblies in Sustainable Minds and Ecolizer resembled what he was accustomed to on CAD tools, making them more intuitive.

Another hurdle I observed was that practitioners were unsure what impact assessment methodologies to select. These methodologies vary by what impacts they measure, how they are weighted, and how they are normalized into a single score. This decision was confusing to new users who were unaware of the inherent trade-offs. GaBi and SimaPro offer various choices such as ReCiPe midpoint, endpoint, and single scores [69] and the TRACI score [70]. Sustainable Minds only computes TRACI, Ecolizer only computes ReCiPe single score, and EarthSmart offers the ReCiPe scores plus their own methodology.

Overall, novice users are least accommodated by SimaPro and GaBi. P1 said, *"I feel like it probably took me eight hours to get to a point where I could even begin to put a model together"*, referring to SimaPro. He added, *"Even then, I am definitely still on the learning curve. I have not got a full understanding of everything."* P1 also used GaBi and had to spend a *"week-and-a-half"* learning how to use it despite prior experience with SimaPro. Participants expressed feeling less confident about the results and hesitant to adopt LCA in their practice, when daunted by tool complexity.

Breadth and Depth of Databases

Practitioners relied on compiled life cycle inventory (LCI) databases when building an LCA model. Some tools (e.g GaBi, SimaPro) offer a wide range of databases, helping practitioners build more robust models. GaBi claims to have the *"largest LCI data industry coverage worldwide"*, offering several industry-specific data modules. I observed that having access to a variety of databases is a key factor influencing tool choice. As P1 put it: *"The only reason we started using GaBi was because of their extensive electronics database."* This ability to utilize comprehensive data may even compel somewhat reluctant selection of a less usable tool, which GaBi was for P1: *"It's easiest to use [GaBi's] databases in their software. If we could easily use their databases elsewhere, then I probably would have done that."*

The industry in which the practitioner operates affects their database needs. For example, participants at Synapse develop consumer electronics products, and were hence dissatisfied when tools failed to provide in-depth and up-to-date electronics data. P1 noted, *"On SimaPro, printed circuit board assembly entries have much broader averages. They don't let you dig into the details as much. The electronics make up over 90 percent of the impact of our products, and we want to have a detailed understanding of what is causing that."* P2 also considered the ecoinvent 2.2 (2010) database on Sustainable Minds to be *"obsolete"*.

Reliability of Results:

Reliability of results generated was found to be another determining factor in selecting an LCA tool. This is largely affected by the following different kinds of uncertainty creeping into results.

First, a tool's complexity coupled with a user's lack of background in LCA concepts can produce inefficiency and erroneous outcomes. Participants described often feeling *"uncertain and confused"* which led to errors during modelmaking, followed by a painful recovery process of trial-and-error until they learned workarounds. P1 described the frustration of such experiences in GaBi, noting, *"I did not know how to do what I wanted to do."* P4 expressed a similar link between uncertainty and capability in using EarthSmart: *"It might be my inability to use this in an efficient way. I find that I'm mostly working around problems rather than figuring them out, maybe in a better way."*

Second, there is inherent uncertainty baked into the inventory databases. Problematically, this hidden uncertainty goes unnoticed, especially by novice users, since tools do not account for it when reporting results. P3 expressed the importance of transparency with database uncertainties because they could impact subsequent decision-making: *"I would like it [the tool] to communicate clearly that there are uncertainties in the databases because I am trying to make decisions based on this."*

Finally, performing an LCA early-on means there will be uncertainty in the information a user inputs. That is, the exact quantities, and choices of materials, processes, and end-of-life pathways may not have yet been determined. Users therefore make estimates and guesses contributing to uncertainty. Unfortunately, none of the tools evaluated allow users to account for the uncertainty in input data when calculating and visualizing impacts, thereby contributing to the *ecodesign paradox* discussed in Sec 1.3.

Effectiveness of Visualizations in Supporting Sensemaking and Communication

Interviews highlighted how participants desired visualizations that support both interpretation and communication of insights, which they can then translate to design decisions. Ecolizer uses a pie chart (Fig 6.d) to represent impacts by life cycle stage. P3 noted that *"it was harder to see"* the small sections of the pie and that such representations were *"not useful when making comparisons"*.

On the other hand, P2 explained that Sustainable Minds aided interpretation by making it easy to recognize the primary contributors to environmental impact: *"It shows that the important area for us to look at here is manufacturing."* She then looked at the part/sub-assembly level stacked bar graph (Fig 6.b) to identify what the exact sources of the impact were. P2 appreciated that the tool allows for comparison across different concepts from the same project.

Besides bar charts, SimaPro represents impacts with a unique Sankey diagram (Fig 6.a), which was received favorably by P1 (e.g., *"It was really useful to communicate the* *sources of the biggest impacts. [I] simply grabbed a screenshot of the chart to share with colleagues."*) SimaPro uses these Sankey Diagrams to illustrate the source, flow, and magnitude of environmental impacts, making it effective for comparisons within the lifecycle of a given product concept to identify sustainability hotspots, although it does not support comparisons across different concepts.

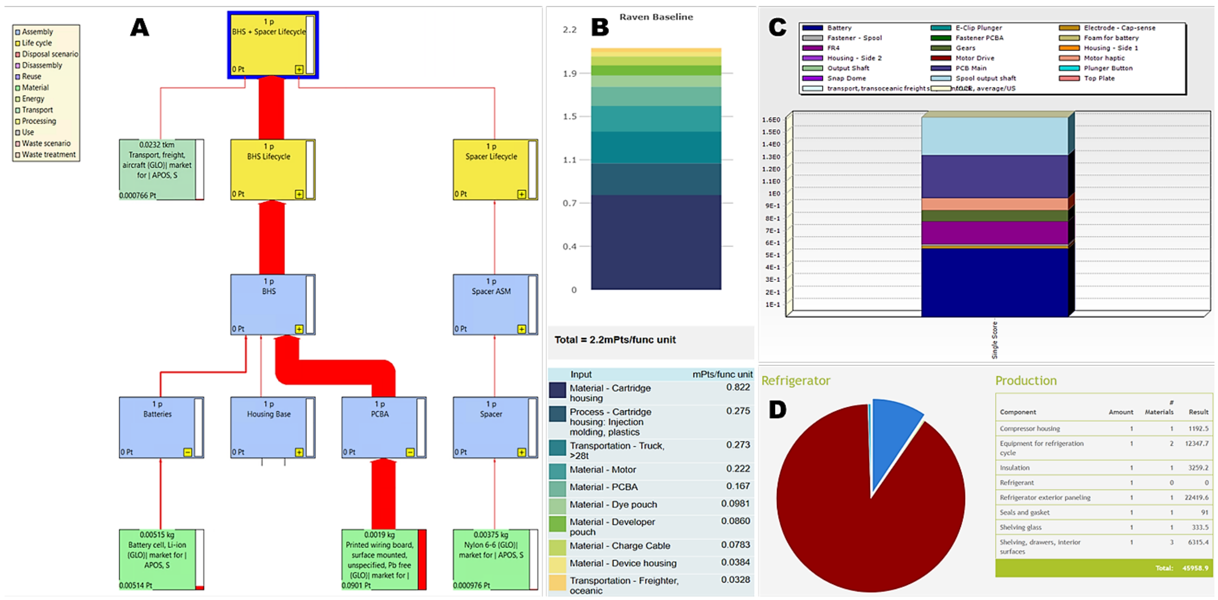

Figure 6: Screenshots of visualizations from tools evaluated: a) SimaPro, b) Sustainable Minds, c) EarthSmart, d) Ecolizer

Standalone Use Capabilities

Participants noted that LCA tools did not fully support their end-to-end needs, leading them to use other tools to fill in the gaps. In particular, all participants preferred to export the data to Excel to generate their own custom visualizations when communicating results. P3 noted that he would review the tool-generated graphs with internal colleagues but transfer to Excel to create graphs for clients. P1 similarly explained how he would *"polish the graph on Excel"* when reporting to clients. Participants agreed on the value for LCA tools to offer additional customization capabilities.

2.1.5 Survey Results

The survey results in Table 2 closely reflect insights obtained from interviews.

Table 2: Participants' rating of LCA tools on five criteria using a 1-5 scale, weighted according to their importance

Tool	**Factor**	Learnab ility	Ease of use	Breadth & depth of database	Reliability of results	Effectiveness of results-visualization	Cost	**Total**
	Weight	0.25	0.25	0.25	0.05	0.15	0.05	
Sustainable Minds		4	4	2	3	3	4	3.3
Ecolizer BE		3	4	3	3	2	5	3.2
SimaPro		1	1	5	5	3	1	2.5
GaBi		1	1	5	5	3	1	2.5
EarthSmart		2	1	4	4	1	3	2.25

Learnability and *ease of use* were weighted highest because time was the biggest barrier to integrating LCA into the firm's PD workflow. Having more flexibility and choice in *databases* was similarly critical to their choice of tool. *Effectiveness of visualizations* was weighted second highest. Participants worked around the *reliability of results* by performing LCAs on multiple tools to validate results. *Cost* was not seen as a significant constraint for this firm. Table 2 provides average ratings. This paper's insights and design recommendations are primarily based on the qualitative interview data, with the ratings summarizing the aggregate attitudes towards each tool.

Sustainable Minds scored highest overall, owing to its short learning curve, relatively intuitive interface, and low cost. Ecolizer came a close second, falling behind on results-visualization. P3 alluded to how the tool only offered pie-chart representations, which were not conducive to making comparisons, and the tool's limited customization capabilities. Being free, Ecolizer scored best on cost.

SimaPro and GaBi scored highest on database offerings and result reliability, which is consistent with their status as industry-standard tools used by experts to generate sustainability reports. Both provide a wide range of database and impact assessment methodology choices. However, both tools were found to be complex, unintuitive, difficult to learn, and expensive, leading to low scores on those factors. Finally, EarthSmart offers more features than Sustainable Minds and Ecolizer, but the additional complexity hurts its learnability and ease of use.

2.1.6 Design Implications

The qualitative insights from my interviews with participants and their subsequent ratings of LCA tools highlight shortcomings of existing tools to cater to the needs of an early-stage product development (PD) context and novice LCA users. Aiming to address these limitations and offer directions for the design of more effective LCA tools going forward, I outlined design prompts in the form of "how might we" questions below:

- *How might we (HMW) managed the time constraints affecting the application of LCA in a fast-paced PD context?* I recommend improving a tool's upfront learnability and ease of use so it can be applied efficiently and effectively.
- *HMW make LCA results more reliable?* I found that trust in results was impeded by uncertainties in input data and the databases, and users' confidence.
- *HMW facilitate iterative refinement of models?* I learnt that iterative refinement of models could be supported by easing error recovery and enabling version control.

- *HMW support interpretation and communication of LCA results?* Successfully translating LCA results into actionable design decisions hinges on enabling sensemaking and communication of these results. I recommend that tools should enable greater flexibility and customizability when visualizing impacts.

Table 3 presents these HMW questions, followed by the identified shortcomings that motivated them, and our high-level design recommendations to address these issues. While not exhaustive, they can guide the creation of better tailor LCA tools for designers.

Table 3: HMW questions and design recommendations for future LCA tools

HMW questions	**Shortcomings**	**Design recommendations**
HMW manage the ways time constrains the application of LCA?	Learnability	Improve familiarity through resemblance with commonly used tools like CAD
		Reduce tool complexity
		Include walkthrough tutorials, tool-tips, etc.
	Ease of use	Limit number of clicks required
		Improve intuitiveness of the process (e.g., by offering a progress bar, hints, etc.)
		Apply design principles from HCI research
HMW make LCA results more reliable by accounting for inherent uncertainties?	Input data uncertainty	Allow users to enter uncertainty values, for the overall model and for individual entries
		Account for the uncertainty in the results visualization
		Highlight overlapping error bars that may prevent false confidence in results
		Allow users to track uncertainty across versions as the product concept matures
	Database uncertainty	Account for the uncertainty in the database
	Lack of confidence	Reduce tool complexity
HMW facilitate iterative refinement of models?	Error recovery	Limit errors by improving intuitiveness
		Flag inputs for review if they seem off compared to the rest of the model

		Allow users to trace an anomalous data point in the visualization back to its source model-making
	Model version control	Allow users to create and manage versions of the model as they progress through PD
		Track changes in input uncertainty and environmental impacts across versions
		Document changes across versions
	Comparisons	Allow comparisons between concepts
HMW support interpretation and communication of LCA results?	Impact assessment options	Allow multiple metrics (ReCiPe single score, ReCiPe midpoint score, TRACI score etc.)
	Visualization format choices	Offer visualization choices (Sankey diagrams and for overviews, bar charts etc.)
	Interactivity and customization	Allow customization of graph aesthetics
		Allow comparisons across sub-assemblies, versions of a model, design concepts, etc.

2.1.7 Study Limitations and Future Work

This study was conducted at a PD consultancy to help integrate sustainability considerations into their practices. My interviews were limited to a small group of participants. Being embedded into the company promoted deep understanding of practices and rich feedback; however, only one interview was conducted per tool. In subsequent studies, we expanded the participant base to include practitioners from other industries. Future studies to evaluate existing LCA tools can consider distributing surveys to a broader group of target users via LinkedIn groups and other professional communities, asking participants to rate the tools on our aforementioned metrics.

In summary, this study investigated the effectiveness of existing LCA software tools in catering the needs of early-stage PD practitioners. LCA as a methodology allows for quantifying impacts across the overall product life cycle, making it a powerful approach for data-driven sustainable design. Rich qualitative feedback gathered through interviews and think-aloud sessions identified factors critical to implementation of LCA in early-stage PD, including: learnability, breadth of databases, reliability, visualizations, and cost. Results revealed that all of the evaluated tools failed on one or more of these criteria, forcing the company to purchase licenses to multiple tools to compensate for the assorted shortcomings. I observed that this not only inhibits practitioners from applying LCA, but also that the associated expenses pose a financial barrier to most.

In subsequent sections, we detail how these design recommendations were applied to design and develop a novel LCA tool that addresses the gaps identified in this study. Essential to my process are human-centered methods, including ongoing engagement with target users to gather feedback on iteratively refined prototypes, and rigorous user testing and eventual deployments to evaluate the tool in real-world contexts.

2.2 System Design

Applying the design recommendations gathered from user research, I co-designed a lightweight LCA tool that is approachable for novices and addresses the *ecodesign paradox* by enabling reliable assessments during the early stages of PD. During this project, I collaborated with This project was undertaken in collaboration with my faculty advisers, Prof. Jeremy Faludi, and Prof. Liz Murnane, and students from the DALI Lab at Dartmouth. We also benefited from expert advice and access to databases and a backend calculation engine from EarthShift Global Inc. (EarthShift), a sustainability consultancy based in Maine. This work is built upon prior work in literature, including the development of FocusLCA at UC Berkeley [71]. Our engagement with these collaborators is further detailed in subsequent sections.

2.2.1 User Journey Mapping and Research Questions

User research and literature review guided by understanding a practitioner's journey through applying LCA early-on in PD to inform design and engineering decisions is illustrated in Fig 7. In addition to assessing and comparing the impact of various design choices (e.g., about material choices, manufacturing supplier selection, energy use, and end-of-life), lightweight LCA results can also guide users about what aspect(s) of a product's life cycle to focus on when aiming to optimize eco-friendliness. Lightweight LCA tools therefore offer the potential to support data-driven and science-based decision-making, meaningful sustainability improvements, lesser greenwashing, and greater accountability in product design. They also illuminate how day-to-day PD choices add up towards higher level sustainability targets. The design, development, and evaluation of EcoSketch was guided by these research questions:

1. How might we design LCA software that is *easy to learn and use*, and is *accessible to non-experts* during early-stage product development?
2. How might such interactive software improve the *overall workflow of performing LCA* in these situations and make sustainable product development *decision-making more efficient*?
3. How might such efforts also help *form bridges between the human-centered computing community and sustainability practitioners* to collaborate on better sustainability design methods and tools for the future?

The process to answer the first question is detailed in this section, while the others are detailed in the subsequent sections.

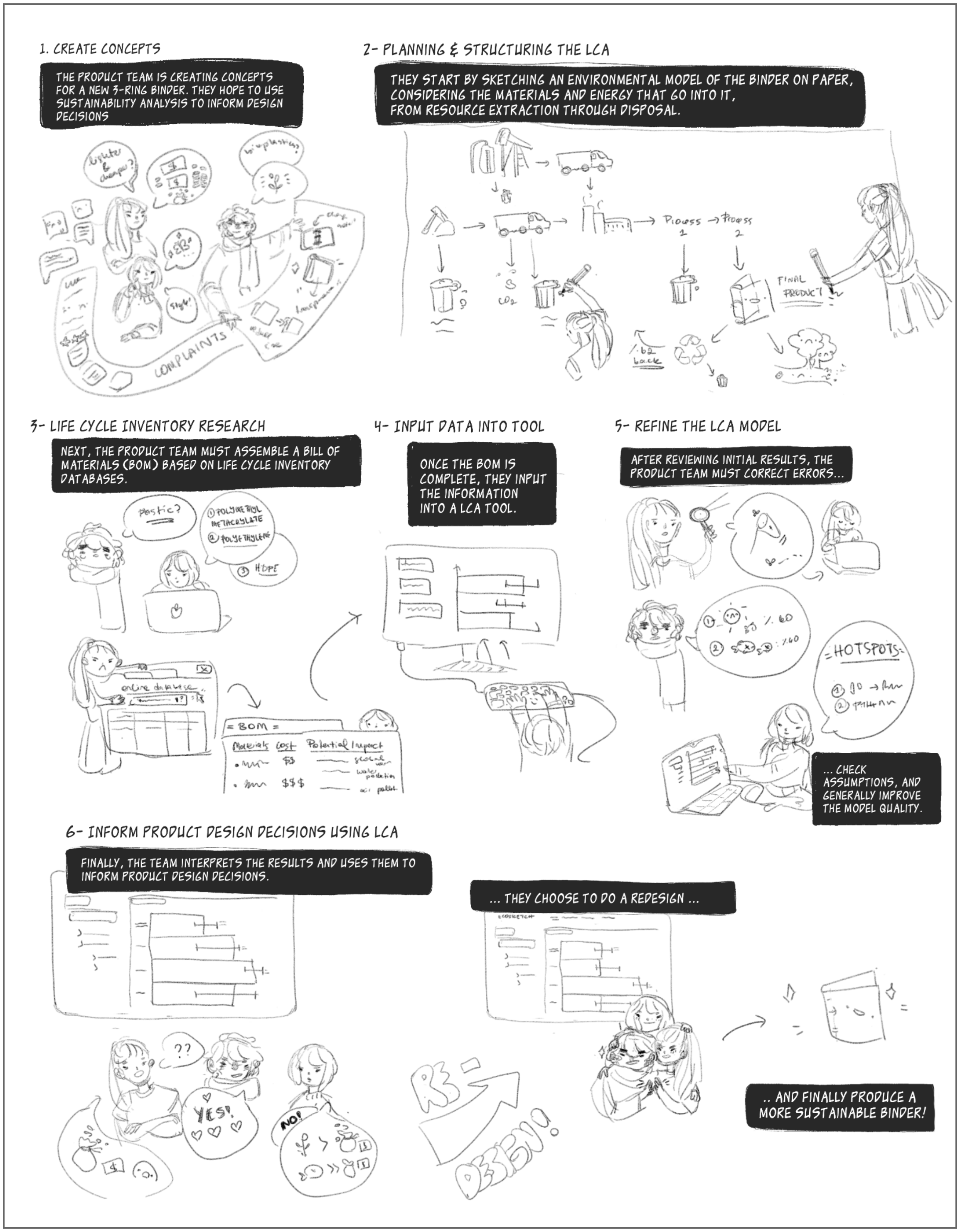

Figure 7: Storyboard detailing the process of performing an LCA early-on in PD

2.2.2 Industry Engagements

Responding to industrial movements towards sustainable product development as well as calls from the sustainable HCI community to promote more systems-wide change through novel informatics tools, we have built on this interdisciplinary groundwork to create the EcoSketch system. EcoSketch is an interactive tool that supports lightweight environmental assessments during early stages of product development (PD).

Our design process for EcoSketch involved iterative needfinding, prototyping, internal testing, and full implementation, followed by an overall system evaluation of the tool's usability and efficiency in a realistic early-stage PD scenario. Our initial formative steps drew on insights from the literature and industry PD practitioners.

First, to gain first-hand understanding of industry contexts and needs and to generate design requirements, I conducted four months of needfinding at Synapse, detailed earlier in Section 2.1. This work confirmed that most existing LCA tools were not applicable for the early-stage PD and often required specialized expertise, highlighting a gap in tools tailored to novice users of LCA. More specifically, we identified that lightweight LCA tools must better support the following needs in order to integrate effectively into early-stage PD:

1. Quick, intuitive, and efficient modeling of product components and impacts
2. Ability to input uncertain data
3. Digestible data visualizations to ease sensemaking
4. Error recovery and version control

Our iterative prototyping of the EcoSketch interfaces and features solicited and incorporated periodic feedback from these industry collaborators. The design and development process lasted a period of two years and followed a rigorous and iterative design process involving three rounds of gathering feedback from PD practitioners. Figure 8 (a, b) shows some examples of earlier prototypes in pencil sketches and low-fidelity Figma versions.

Figure 8 (a): pencil sketch prototypes of EcoSketch; (b): low fidelity Figma prototypes

Once we reached the stage of functional implementation, we further sought the input of LCA professionals at EarthShift whose staff of experienced LCA professionals conduct LCAs, provide LCA coaching services, and develop heavyweight LCA software. They have been involved throughout our design and development process, particularly to guide EcoSketch's backend and eco-impact calculation engine and to help ensure that EcoSketch offers users appropriate analytic outputs. Notably, I forged a relationship with them that extends beyond the development and evaluation of EcoSketch and additionally involves a deployment pipeline in order to support the future integration of EcoSketch into their suite of LCA software offerings that are used by actual industry clients.

2.2.3 System Components

Translating identified practitioner needs into specific functionality for sustainable design sensemaking, EcoSketch comprises the following main interface components: 1) a model-making canvas, which is also the main workspace and enables input of the uncertainty associated with various product details; 2) a database that contains the environmental impact factors for various inputs related to materials and processes (e.g., product manufacturing, transportation, etc.) that a designer may be considering and aiming to compare for a new product; and 3) a visualization page that displays the results from the environmental assessment calculation. This process mirrors and supports the stages of an LCA process, wherein users start by setting their design goals and scope, then compile data inputs for the quantitative LCA model, assemble this model, and finally run the environmental assessment analysis. Figure 9 illustrates how EcoSketch's components interact with each other to enable users to perform simplified LCAs during product development.

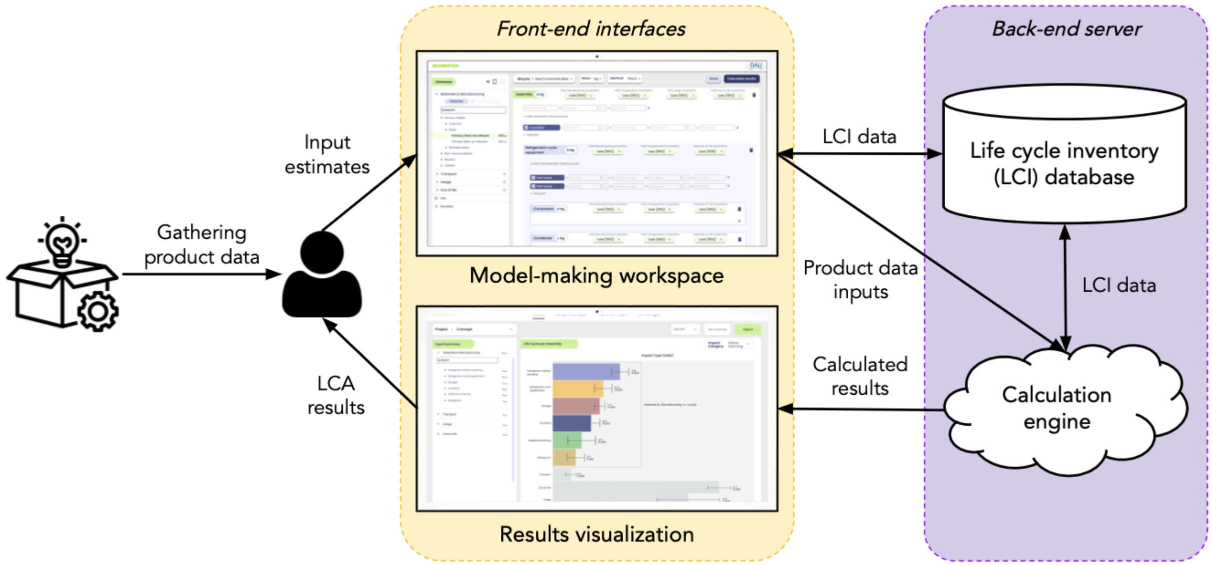

Figure 9: High-level system architecture of EcoSketch showing how the main components connect and interact with each other.

Each of these main components went through a highly iterative design, prototyping, and testing process. The following subsections elaborate on the role of each of these components in performing a successful LCA, and provide screenshots of the interfaces.

Model-making Canvas

In order to perform an LCA, practitioners must model environmental impacts by gathering data on the material and energy inputs and outputs at each stage of the product's life cycle, which spans material extraction, manufacturing, use, distribution, and end-of-life. In EcoSketch, the representation of this LCA model resembles the hierarchical structure used in computer-aided design tools, which will be familiar to most product designers and engineers, where the lowest level in the structure is a "part". Collections of parts combine together into "sub-assemblies", and all the sub-assemblies combine to make an "overall assembly". These inputs altogether form the product's "bill of materials" (BOM). A BOM is a comprehensive inventory of materials, parts, sub-assemblies, and assemblies including quantities and costs compiled by engineers during PD. To create a complete BOM, users input details of parts and sub-assemblies envisioned for each stage of the product's life cycle. These inputs are often in units of mass (kg or lbs) for materials, manufacturing, and end-of-life, electricity consumption (in kWh) for use, and distance (km) for distribution. Figure 10 shows the model-making workspace on EcoSketch where users would supply BOM information to generate results on environmental impacts.

Users spend a majority of their time during the LCA process on this screen, putting their model information together. It is therefore vital for lightweight LCA tools like EcoSketch to make the model-making process intuitive and as easy to use as possible.

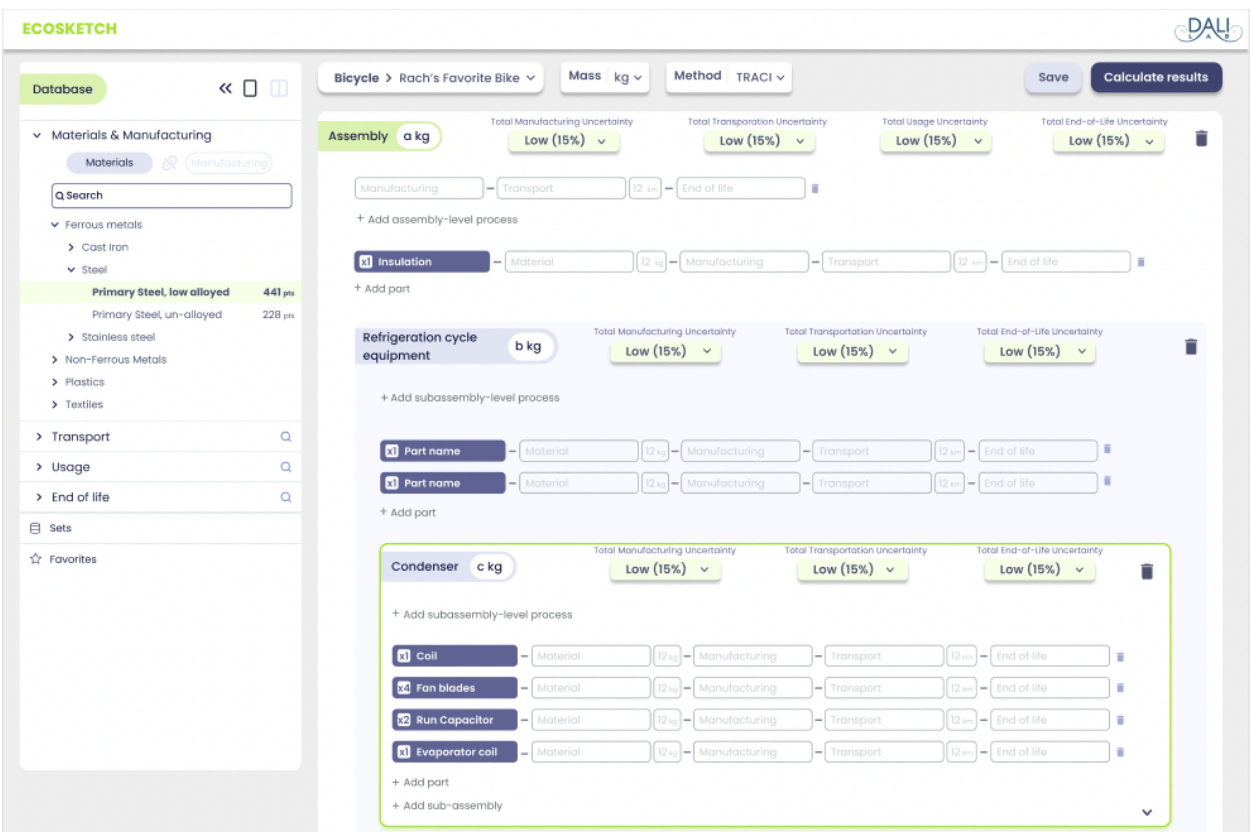

Figure 10: EcoSketch's model-making canvas

To improve ease of model-making, we incorporated the following design decisions as informed by user feedback.

- *CAD Hierarchy:* To foster immediate intuitiveness, the model is organized according to structures and terminology similar to the computer-aided design (CAD) tools that PD practitioners use and already have familiarity with. Specifically, EcoSketch organizes a model of a product by parts grouped into sub-assemblies, and sub-assemblies grouped into assemblies. This is different from flows, parameters, and processes that traditional heavyweight LCA tools use, which practitioners indicated they found difficult to adapt to.
- *Matching mental models by organizing by parts rather than life cycle stages:* The CAD structures further lend themselves to inputting data by parts and sub-assemblies instead of by life cycle stages. We found that this approach makes data entry easier for practitioners because the BOM document used to compile product information follows the same structure.
- *Unfamiliar terminology:* EcoSketch replaces specialized terminology from life cycle inventory (LCI) databases with language that is more familiar and commonly used by practitioners, for example, using “ABS” instead of “acrylonitrile-butadiene-styrene”. To remain universally flexible, however, EcoSketch’s search function supports search by both specialized LCI terms and colloquial PD terms. Therefore, EcoSketch incorporates not only structures but also terminology from CAD to ease practitioners’ learning curve.
- *Linking PD processes to product materials:* EcoSketch links relevant manufacturing processes to each material, thereby simplifying the process of

searching and sorting through the massive LCI databases. For example, if a part is made of ABS, the tool recommends salient manufacturing processes such as injection molding.

Underspecification and Uncertainty Quantification

Work by [72], [73] highlights the promise of probabilistic under-specification as a mechanism for streamlining LCA. In this context, "under-specification" refers to using a more general material category during LCA modeling rather than a more specific one, in order to reduce the time it takes to conduct life cycle inventory (LCI) examinations. Under-specification also naturally lends itself to early-stage PD, when such specifics have not yet been finalized. To make this concept more concrete, imagine an example where a practitioner is modeling a 3-ring binder, which contains metal rings and is otherwise composed of plastics. If the practitioner lacks full information about these specific materials (e.g. the metal may be steel or aluminum, recycled or virgin, and so on), she could choose to under-specify their identities, simply referring to metal and plastic. Upon running the analysis, she would find that the impact of the metals is high, and that under-specifying the metal introduces a high degree of uncertainty into the analysis, thereby learning that conducting further LCI research is in fact merited to determine the precise identity of the metal. On the other hand, the practitioner may discover that the impact and uncertainty associated with the plastic are low, enabling her to save time by forgoing further LCI research to nail down the plastic's precise identity at this point in the analysis.

Given this significant potential for streamlining and simplifying LCA through the use of underspecification, we designed two key features in EcoSketch that allow users to under-specify their data inputs. One enables the input of uncertainty levels, and the other allows a user to group multiple potential design options into sets that can be compared during modeling:

- *The uncertainty feature* allows users to under-specify their numerical inputs (mass in kg, transportation in tonne-km etc.) by providing an option to attach a "low", "medium", or "high" level of uncertainty to these values. In this way, users can effectively create a range of design possibilities around the input value on which to run an assessment. This uncertainty is visualized as error bars in the results.
- *The sets feature* supports under-specification related to the choice of materials or processes, by enabling users to group several options they may be considering, and compare the impacts across these choices when visualizing results. If a part within the set is identified as a significant contributor to the overall impacts, the practitioner can then work on more precisely specifying their material choice on the next design iteration. On the other hand, if a part within the set is not a significant impact contributor, it can remain under-specified and allow the practitioner to focus effort on better specifying the main contributors.

These features together focus on supporting under-specification during initial LCAs, thereby allow users to skip the time-consuming step of gathering accurate data on every element of the BOM, to instead make a quick pass through the assessment to get a sense of potential environment hotspots to hone in on better specifying and refining in subsequent design and analysis iterations.

Database

The database portion of an LCA tool includes the LCI databases, from sources such as ecoinvent [74], that compile the environmental impact factors for a wide variety of materials and processes. For EcoSketch, we use data from ecoinvent3, which is compiled by a not-for-profit organization dedicated to providing data for sustainability assessments. Building an LCA model in our tool involves selecting appropriate product materials and PD processes from the database, as illustrated in Figure 11.

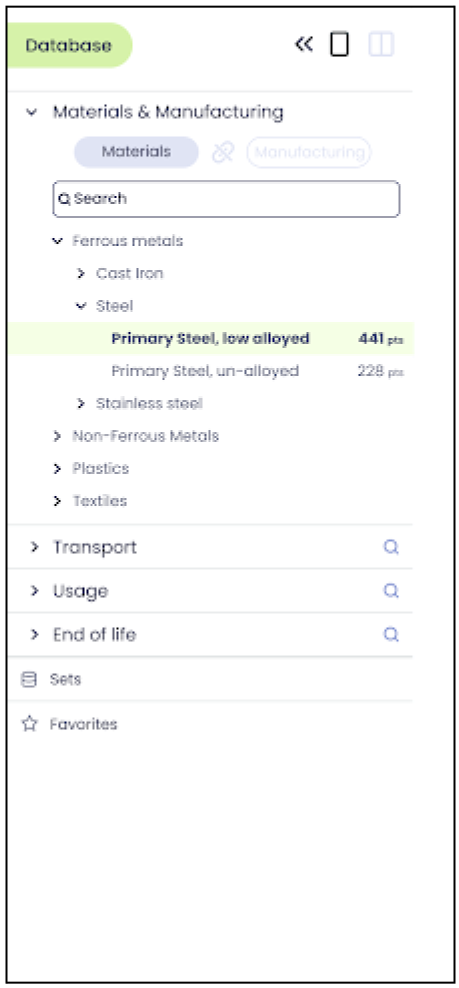

Figure 11: EcoSketch's back-end includes a database based on ecoinvent3, which compiles the environmental impact factors for various materials and processes

Visualization Page

Finally, the visualization page is where users can view the results of their LCA in order to evaluate the sources of the biggest environmental impacts, with panes to organize and drill into impact according to part, sub-assembly, and life cycle stage. We explored a variety of data visualization formats during our design process, eventually landing on the final design illustrated in Figure 12 (A, B, C) to communicate the environmental impacts in a way that we found was comprehensive yet still manageable and easy to understand. Specifically, to improve users' ability to make sense of an LCA, particularly novice users and LCA non-experts, we made the following design decisions for the visualization page, with a focus on how to best account for and represent uncertainties in the results and to avoid giving users the illusion of false precision.

- *Uncertainty visualization:* To convey uncertainty in calculated environmental impact results, EcoSketch uses error bars. Several other formats were considered including blurs, triangles, and box-and-whiskers; but we settled on error bars based on prior research suggesting that practitioners preferred them over other formats [75].
- *One impact category at a time:* Earlier versions of EcoSketch included a graph that showed the environmental impacts across 18 different categories (e.g., global warming, freshwater eutrophication, terrestrial ecotoxicity, etc.) relative to each other on a percentage scale. However, upon user testing this visualization, practitioners said they found it *"confusing and difficult to understand"*. Based on this feedback, we designed all graphs in the visualization page to focus on one impact category at a time to avoid information overload.

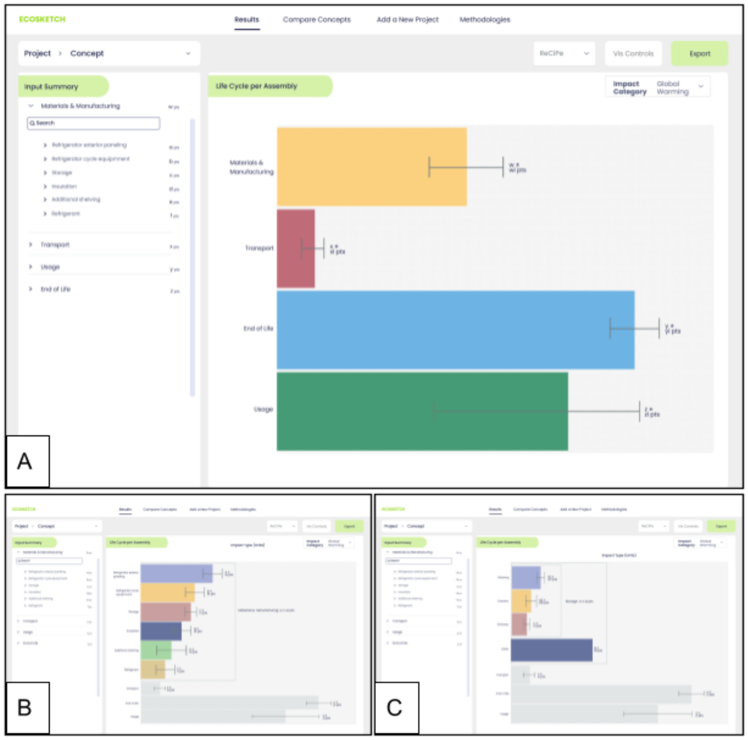

Figure 12: Graph A displays the overall environmental impacts by lifecycle stage. Clicking on one of the bars lets users dig down to the sub-assembly level (B), and part-level (C) impacts.

Employing HCI principles to enhance user experience

This subsection overviews the various features and design decisions made based on established usability heuristics [66], to improve the user experience of EcoSketch.

1. Flexibility and efficiency of use:
    a. Better nesting and alignment: Collapsible sub-assemblies allow users to scroll through a complex model with ease.
    b. Reorganization: Parts and sub-assemblies can be moved by dragging and dropping them to reorganize model structure and hierarchy.

2. Recognition over recall:
    a. Easy access to favorites: The tool allows users to save frequently used materials and processes to favorites folder for easy access.
    b. Eliminating separate windows: Most existing LCA tools use a separate pop-up window to display the database for selection of materials and processes. Practitioners complained that this was “inefficient” and “makes me forget what I am inputting data for”. EcoSketch avoids this issue by presenting the database options adjacent to the model so users can directly see and manipulate the model by dragging inputs from the database.
    c. See the full picture: Instead of using separate tabs or screens for different life cycle stages, as most tools do, EcoSketch lays out the entire model in a one-stop-shop screen to simplify practitioners’ modeling workflow.
3. Aesthetic and minimalistic design:
    a. Search bar color and position: Our user testing with a high fidelity prototype showed that people struggled to find where the search function was located. Most users failed to notice the feature altogether and manually searched the database during testing. We therefore created a higher-contrast search bar that is more noticeable, as shown in Fig 11.
    b. Dig deeper into the same graph: Instead of looking at multiple graphs, users can visualize impacts from lower levels of hierarchy in the same graph. A sub-assembly bar dynamically breaks down into its constituent parts when clicked, as shown in Figure 12.

Altogether, we designed EcoSketch to allow users to nimbly explore in the face of uncertainty during early-stage PD, quickly visualize and understand the greatest environmental impacts surfaced by the LCA, and generally derive insights that can be acted on during subsequent PD phases to iteratively refine product choices and processes to enhance sustainability. We hypothesize that our approach will save the user time, keep the tool usable for LCA non-experts, and enable overall effective performance at completing LCAs during early PD stages. We will test this during our system evaluation.

2.3 System Evaluation

Our evaluation of EcoSketch focused on answering the research questions outlined in Section 2.2.1, which relate to the tool's usability for LCA non-experts, and its ability to improve the efficiency of environmental assessment workflows during early-stage PD decision-making.

Seeking a sample of participants representative of product designers and engineers who are novices in LCA, we recruited N=46 graduate and undergraduate engineering students with experience working on product design projects for classes, internships, and/or personal projects. These individuals were all screened as good proxies to the industry professionals we had interacted with throughout our formative and iterative design phases, based on the similarities in their qualitative reactions and feedback. The Anonymized Institutional Review Board reviewed and approved all procedures.

To begin the study, participants consented to grant permission to record voices as part of the my observational analysis of people's user experiences during the study. Participants were then introduced to basic LCA concepts and their application in a PD context, and we asked preliminary questions to assess background with LCA, including:

- What is your level of experience with LCA?
- How many times have you built LCA models in the past?
- Which design tools and environmental assessment tools have you used before?

Following the recruitment of participants, I applied qualitative and quantitative research methods to answer the following research questions:

1. How might we design LCA software that is easy to learn and use for non-experts during early-stage product development?
2. How might such interactive software improve the overall workflow of performing LCA in these situations and make sustainable product development decision-making more efficient?
3. How might such efforts also help form bridges between the human-centered computing community and sustainability practitioners to collaborate on better sustainability design methods and tools for the future?

2.3.1 Qualitative and Semi-Quantitative Methods - Research Question 1

As a reminder, our first research question aimed to evaluate the usability of EcoSketch, as a tool designed to be accessible for use by non-experts during early-stage product development. The tests conducted to answer this question focused on gathering qualitative and semi-quantitative data on participants' user experience with LCA tools.

Participants were provided with a sample bill-of-materials (BOM) table for a simplified refrigerator, similar to the level of fidelity one might be working with during early stage PD. The table contained names of the constituent parts and sub-assemblies, the materials those components are made of, their quantities (in kg), and their manufacturing processes. All participants then received a walkthrough tutorial about EcoSketch and were asked to employ the BOM to navigate EcoSketch during a think-aloud study.

Specifically, we used the Boren & Ramsey protocol for the think-aloud, where the participant and the test administrator engage in essentially an asymmetric dialogue, with the participant doing most of the talking. This protocol allows test administrators to acknowledge participants' contributions and offer encouragement, as needed, to help participants continue verbalizing their thoughts and feelings [67]. In our case, participants were asked to think out loud as they input the data from the BOM into the model-making pages of EcoSketch. They were encouraged to share their thoughts, feelings, questions, areas of confusion, and anything else that came to mind as they performed the activity. Afterward, they were asked a series of semi-structured questions:

- On a scale of 1-10, how easy do you think this tool is for novice users to learn?
- Which aspects of the tool did you find the most useful? Why?
- What aspects of the tool did you *not* find useful? Why?
- Which aspects of the tool did you find the most intuitive? Why?
- Which aspects of the tool did you find the most confusing? Why?
- How well did this tool align with your thought process and mental models as a design engineer? Where did it diverge?

Before moving on to the next part of the study, the System Usability Scale (SUS) survey [76] was completed by all participants except one (began but never completed) in order to measure perceptions regarding the tool's effectiveness, efficiency, and satisfaction.

2.3.2 Quantitative Methods - Research Question 2

Next we examined our second research question, which tests whether EcoSketch enhances the workflow efficiency of using LCA in early-stage product development, particularly due to the under-specification features described in Section 2.2.3. A key observation from our needfinding with industry was that practitioners are highly constrained on time. Hence, for LCA to be effectively adopted, it is important that it can be performed rapidly.

Our evaluation followed a between-subjects study design that compared EcoSketch to a "control condition" tool called Ecolizer. In choosing a state-of-the-art comparator, we narrowed to either Ecolizer or Sustainable Minds, which are geared for the PD context and are two of the highest-rated tools available, according to prior work [14]. Sustainable Minds, however, requires costly individual licenses, making it infeasible to employ for our study and more generally limiting its accessibility as a lightweight LCA tool. Ecolizer on the other hand is a free web-based simplified LCA tool, making it an ideal comparator for evaluation. Figure 13 shows screenshots of Ecolizer's workflow. From here on, Ecolizer is referred to as the "control tool".

The interaction flow charts in Figure 14 illustrate the difference in LCA workflow that the introduction of uncertain inputs creates in EcoSketch vs. the control tool (Ecolizer). Following preliminary product design stages (e.g., problem definition and idea generation) for EcoSketch's workflow (Flow A) involves users conducting a preliminary LCA with uncertainties permitted in their choice of materials and quantities.

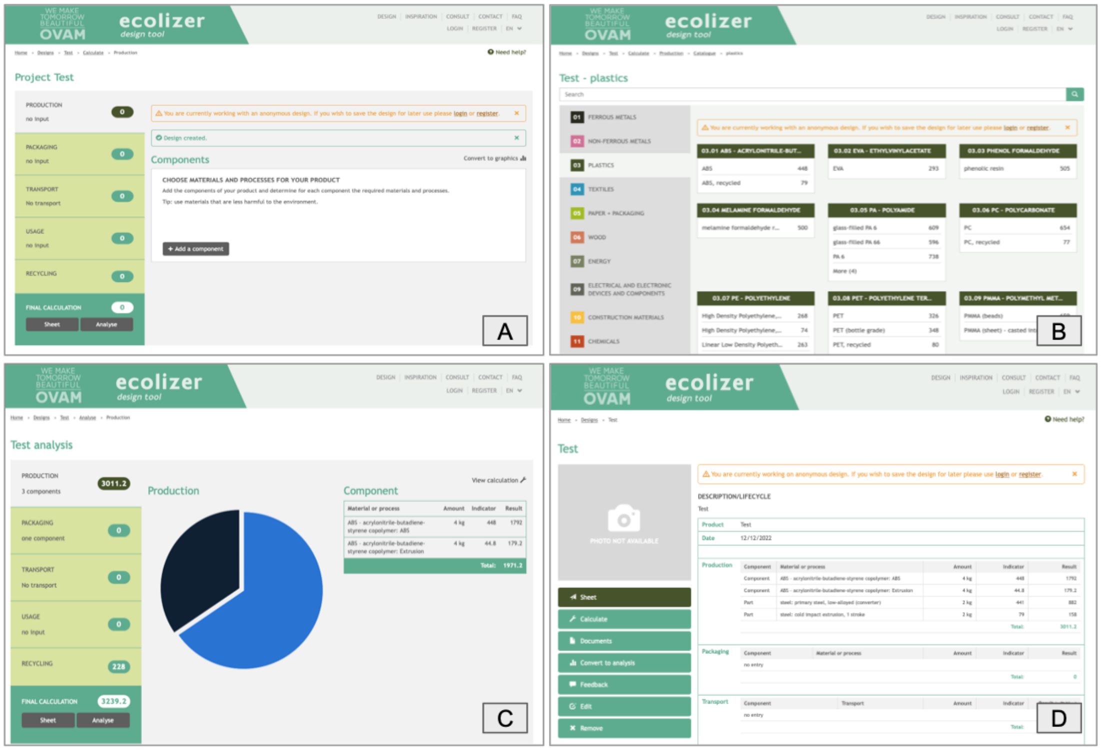

Figure 13: Screenshots from the control tool depicting A: model-making, B: LCI data input, C: results visualization, and D: report making

EcoSketch accounts for these uncertainties to calculate estimates of environmental impacts from each part, sub-assembly, and life cycle stage. These estimates help guide practitioners to focus on the PD aspects contributing the most environmental impacts, which can be specified further with precision in subsequent design and LCA iterations, rather than specifying every single data input. Later product design stages then incorporate design strategies addressing the hotspots identified. This approach potentially reduces the time spent on the data collection and preparation step by taking a more streamlined and iterative approach.

Similarly after preliminary PD stages, the control tool's workflow (Flow B) then deviates because users must next perform a thorough data collection and preparation step. Given users are unable to enter uncertain data inputs, they are forced to be precise upfront and spend more time on data collection. Users then use the more precise LCA results to inform the sustainable design strategies incorporated in later product design stages.

To test the differences in workflow efficiency between these two approaches, participants were randomly assigned to work with either EcoSketch or the control tool (N=23 participants used EcoSketch, and N=23 participants used the control tool). To ensure participants in both groups were equally familiarized with their tool, participants in the Ecolizer condition underwent a 15-minute workshop about this tool.

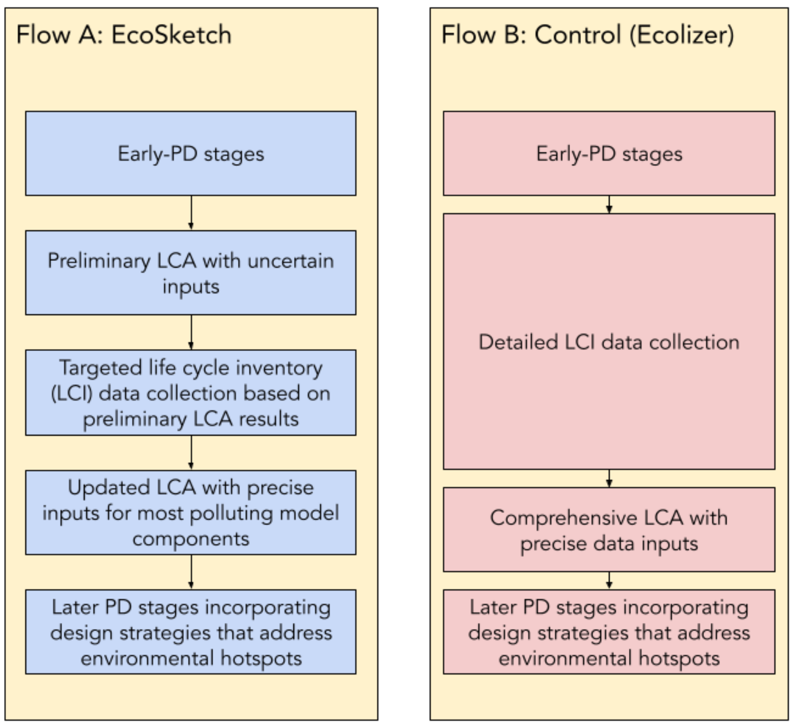

Figure 14: Interaction Flow A illustrates the EcoSketch LCA workflow which integrates uncertainty and sets features to support underspecification. Interaction Flow B shows the traditional LCA workflow used by existing tools like Ecolizer - our control tool

The workshop involved the test administrator walking through Ecolizer's interface to input data from the BOM used in the prior think-aloud test as participants followed along on their computers.

Next, participants were provided with a new sample project, included in the Supplementary Materials, with a defined product concept for a chair including an image depicting what it might look like. Participants were asked to use the internet and other resources to put together a BOM for the LCA with as much detail about the material choices, quantities, and manufacturing processes as necessary. Participants were given a maximum of 60 minutes for the task. Before beginning the task, participants were given the opportunity to resolve questions or confusion that might have confounded performance of the task. All participants were timed, and several participants completed the task well before the end of the session.

Upon completion of the activity, participants were asked to self-assess the precision of their input data as well as the completeness of their model, both on a 1-5 Likert scale. Inspecting a random subset of these models, a co-author and I agreed with these completeness ratings, indicating the reliability of the self-reported data. Participants who used EcoSketch were further asked to describe their perceptions about the EcoSketch-specific uncertainty and sets features, to help ensure that participants utilized those features appropriately and as expected.

2.3.3 Data analysis

Thematic Analysis of Qualitative Data

Recordings from the think-aloud test were transcribed and thematically analyzed by the authors [68]. Specifically, two coders reviewed the transcripts and generated initial qualitative codes, which were iteratively discussed, refined, and combined into higher-level themes.

Data Pre-Processing

The LCAs conducted by participants during the between-subjects experiment were reviewed by the authors who are proficient in LCA. Six of the total 46 participants were deemed to have not performed the analysis correctly, so we excluded their data from analyses. For example, these participants either grossly overestimated the input values (which suggested they did not in fact have sufficient product design background to be representative of our target user base) or did not complete the tasks conscientiously and in good faith. This happened both with the EcoSketch group and the control group.

In the next section, I report on insights from our user study designed to answer research questions regarding whether EcoSketch's approach (1) is usable for novice users without specialized LCA expertise and (2) supports efficient environmental assessments during early-stage product design workflows.

2.3.4 Research Question 1: Factors Contributing to Usability for Novice Users

Our think-aloud testing helped us observe how users interacted with the EcoSketch interface and gather participants' thoughts, questions, and recommendations. Specifically, our thematic analysis reveals that the following tool characteristics are of prime importance to users when applying LCA in PD practice: flexibility of use, learnability, accounting for uncertainty, intuitive sensemaking of results, and quick error recovery.

Thematic analysis and qualitative insights

Here we elaborate on how we observed that specific EcoSketch features and design strategies contributed to these aspects of the LCA experience. Table 4 then connects these themes to the practitioner needs we had originally identified and provides representative participant quotes for richer context. We include both positive and negative participant reactions, with negative comments further giving a window into aspects of LCA that may be especially challenging, along with potential avenues for additional improvements.

1. Flexibility (F): Participants saw EcoSketch as a flexible tool that enabled agile manipulation of information during LCA, in large part due to how the tool provides the ability to easily reorganize the model structure and hierarchy.
2. Learnability (L): We found that participants' ability to learn how to use EcoSketch was supported by incorporating familiar structures and terminology from PD (such as CAD conventions), and eliminating the use of hyper-specialized, LCA-specific terminology and notations as much as possible.
3. Accounting for Uncertainty (U): EcoSketch allows users to perform LCAs with limited product knowledge, by making space for uncertain inputs and outputs to encourage rapid, iterative exploration of sustainable design considerations.
4. Easy Sensemaking of Results (R): Using digestible visualizations that highlight the environmental hotspots and conveying the underlying uncertainty of the model were instrumental in making LCA accessible to novice users.
5. Error Handling (E): Finally, we observed the value of including features to prevent common errors and to facilitate quick recovery from errors that are made.

Table 4: Connecting user needs with relevant design decisions, representative user feedback, and themes extracted from qualitative data analysis

Target need	**Features**	**Representative user reactions (positive)**	**Representative user reactions (negative)**	**Themes / strategies**
Improve ease of model building	Use of CAD hierarchy	*"I think the use of CAD trees works pretty well for me…"*	*"I would like it if you could move this part underneath another subassembly "*	F, L

	Input by parts	*"I like that the layout is horizontal, you can input material, manufacturing, and transport for a part…I think it works pretty well actually"*	*"It would be nice to copy and paste a part you created in one subassembly into another"*	F, E
	Linking relevant processes to materials	*"I like that you can see linked processes for materials if you want to or see the whole list by unlinking them"*	*"Confusing that materials and manufacturing are next to each other, but the rest of the lifecycle stages have separate tabs at the bottom"*	F
	Eliminating unfamiliar terminology	*"I didn't know ABS stands for acrylonitrile butadiene styrene! How do you pronounce it?"*	*"ABS could also mean 'anti-lock braking system'. Are there acronyms of materials that could mean multiple things? … would be useful if the full name popped up when I hover"*	F, L
Allow users to input uncertain data	Uncertain quantitative inputs	*"I'm really not sure about the weight…is it two kilos or five?", "I'm going to go with an lower average of 3.5 kg for the polypropylene part and see", "I like making estimations using Google for a quick*	*"Not sure how to represent this in uncertainty levels", "the dropdown with levels feels simplistic", "Would be useful to see the numeric range that a level translates to"*	F, U

		analysis"		
	Material and process selection by sets	*"It's useful to choose a group of hard plastics instead of picking one"*	*"What on earth is a valid set? Can I put anything in it?", "Does the tool automatically calculate uncertainty when I use a set?"*	F, U
Improve data visualization for easy sense-making	Visualizing uncertainty in results	*"The error bars are showing me that there is no precise output value, and are easy to understand"*	*"When I hover over the error bar, I want to see the range of numbers"*	F, U, L, R
	Highlighting overlapping error bars	*"nice to have guidance on how to interpret error bars"*	*"Too many parts are highlighted and it's distracting"*	F, U, L, R
	Displaying one impact category at a time	*"I understand looking at global warming impacts of the product and breaking it down to its parts"*	*"[the graph displaying multiple impact categories] is confusing and the least useful"*	F, U
Allow faster error recovery	Calculating total mass for each sub-assembly	*"I like to deal with errors right away. This makes sure I don't forget a part"*	*"Not clear what this number is doing…"*	F, E, L

System Usability Scale (SUS)

Results from the SUS survey help inform how usable the EcoSketch system is and where the opportunities for improvement lay. Figure 15 represents participant responses on a scale of 1 (strongly disagree) – 5 (strongly agree) to the following ten statements:

- Q1: I think I would like to use this system frequently.

- Q2: I found the system unnecessarily complex (reverse scoring).
- Q3: I thought the system was easy to use.
- Q4: I think I would need the support of a technical person to be able to use this system (reverse scoring).
- Q5: I found that the various functions in the system were well-integrated.
- Q6: I thought there was too much inconsistency in the system (reverse scoring).
- Q7: I would imagine that most people would learn to use this system very quickly.
- Q8: I found the system very cumbersome to use (reverse scoring).
- Q9: I feel very confident using this system.
- Q10: I needed to learn a lot of things before I could get going with this system (reverse scoring).

The aggregated SUS score was 66.45, which indicates a passable level of usability – though we believe that there is value in interpreting this data at a more granular level. Notably, at least 50% of participants expressed 'Agree' or 'Strongly agree' sentiments for nine of the ten questions.

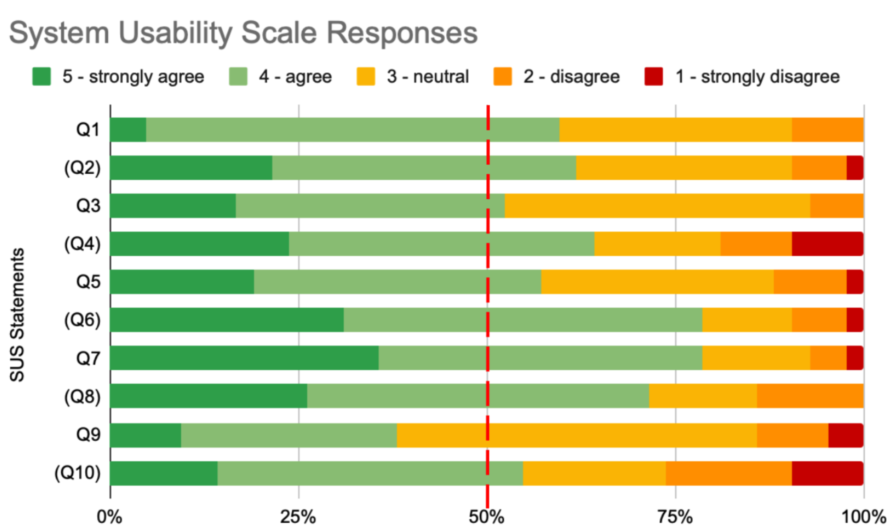

Figure 15: Stacked bar chart displaying results from the SUS survey

Responses to several questions are worth calling out. Specifically, Q6 and Q7 received the most favorable responses, pointing to the EcoSketch's high overall consistency and learnability, respectively. This is corroborated by responses to Q5 and Q10, which similarly relate to the system's coherence and learnability for first-time users, respectively, and also received majority positive responses. Responses to Q2, Q3, and Q4 demonstrate that EcoSketch was not perceived as too complex or technical and was mostly easy to use, which helps to confirm that the tool generally managed to achieve the lightweight user experience we had intended. Finally, Q9 about user confidence saw the least positive responses, which is rather expected considering our participants (engineering students) are a proxy for industry professionals and therefore less routinely engaged with sustainable product development practices. Overall, these ratings and participants' qualitative comments help identify specific ways to improve the usability of lightweight LCA tools like EcoSketch. We reflect on such potential design improvements in the Discussion section.

2.3.4 Research Question 2: Efficiency Gains from EcoSketch's Under-Specification

As a reminder, our between-subject experiment compared the difference in time taken to complete an LCA activity for participants using EcoSketch, which provided under-specification features to support early-stage PD decision-making, versus participants using the control tool, a popular existing simplified LCA tool. At the end of this task, participants were asked to rate the precision of their inputs and the completeness of their models on a 1-5 Likert scale.

Figure 16 strikingly illustrates how participants using EcoSketch were able to build their LCA model from an early-stage concept more quickly than participants using the conventional tool. This difference in time is statistically significant according to a Mann Whitney U-Test (p=0.00000005).

Central to our strategy in the design of EcoSketch was supporting lightweight assessments by letting users input uncertain data to rapidly derive sustainability insights about preliminary design options, which can then be iteratively refined and finalized. To examine whether relieving the requirement to input precise data does contribute to EcoSketch's efficiency, we compare the time participants took to complete their LCA against the level of precision of the data they input into the model. Figure 17 illustrates the results. Indeed, we can see two clusters, one demonstrating how EcoSketch participants are able to input less precise data, which may explain time savings, whereas users of the control tool trend towards more precise inputs and longer time consumption.

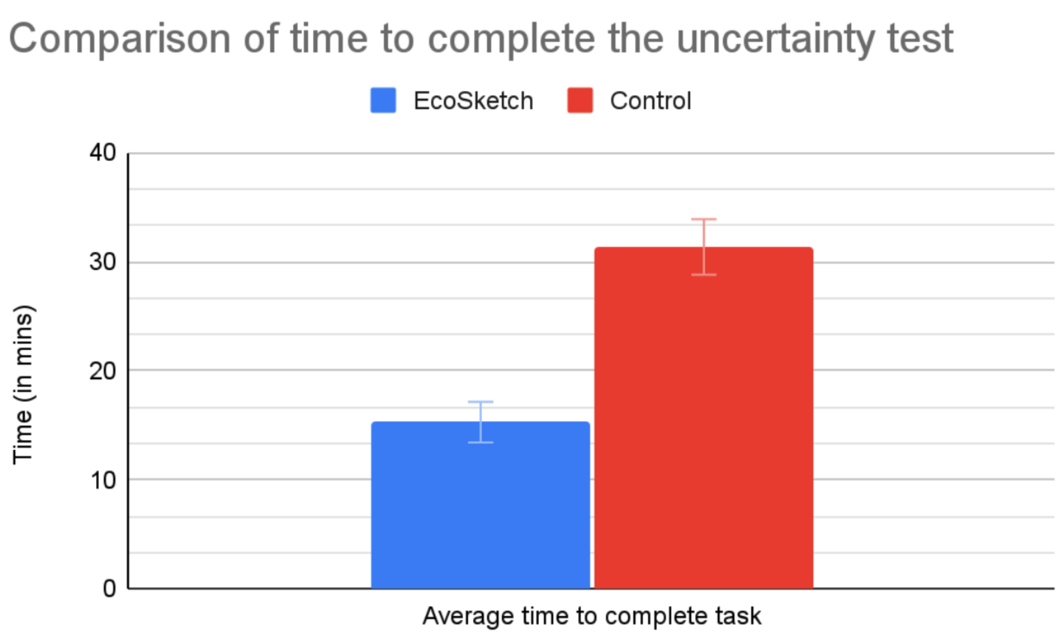

Figure 16: Average time taken to complete a model using EcoSketch (left) vs a popular existing lightweight LCA tool used as a control

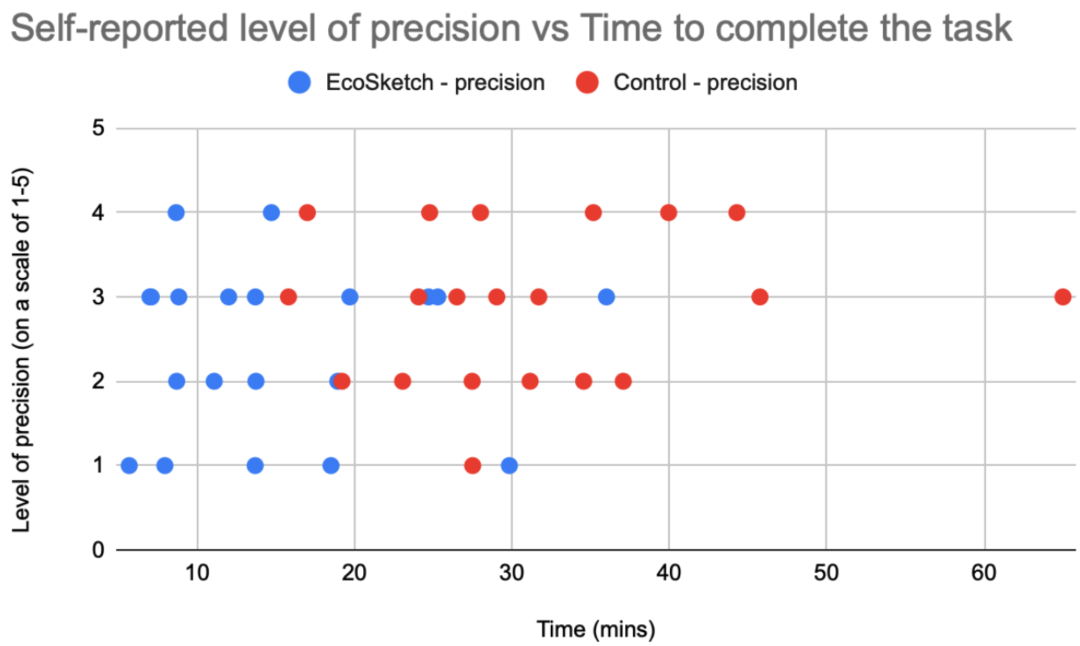

Figure 17: Scatter plot of the relationship between time to complete the LCA and precision of the input data. Observable clusters of EcoSketch vs control users suggest that relieving conventional tools' requirement to input precise data may help save time

Finally, we analyzed data about the level of completeness that participants were able to achieve in their model during the hour-long study session. As seen in Figure 18, participants using EcoSketch were able to achieve a slightly greater average level of completeness in their LCA models compared to users of the control tool.

Taken altogether, these results are highly encouraging, as they indicate that EcoSketch supports efficient and robust environmental assessments by enabling users to perform an LCA more quickly, without sacrificing completeness of modeling results.

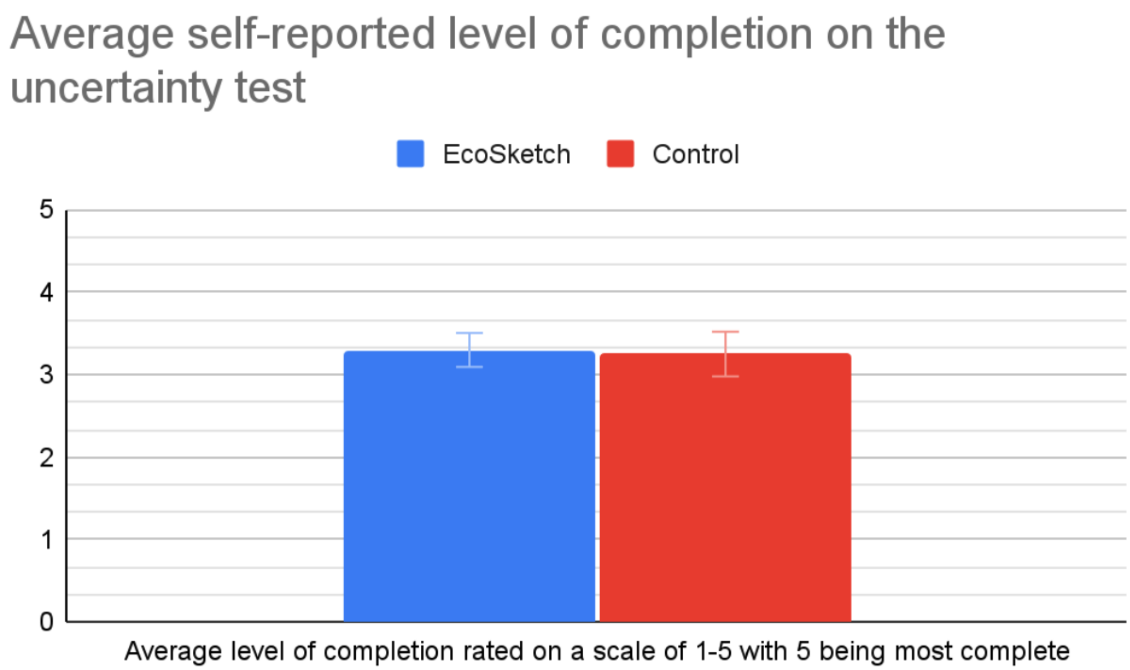

Figure 18: Average level of model completion that users of EcoSketch (left) vs. users of the control LCA tool (right) were able to achieve during the study session

2.3.5 Research Question 3: Bridging the human-centered computing and the sustainability practitioner communities

This research illustrates how HCI researchers and developers can do extremely valuable sustainability work by building better digital tools for industry. By focusing efforts on improving the design and engineering process for a company, HCI researchers can help improve every product that company makes moving forward. For example, prior work has demonstrated how a single project co-creating better sustainability methods for a design consultancy directly resulted in the improvement of four products' designs within two years, cutting projected environmental impacts by up to 38%, plus boosting the company's commitment to improve dozens or hundreds of future products [8], and is detailed in the next chapter.

Sustainability experts have indeed called for HCI expertise in their development of tools for product design, manufacturing, and life cycle management. A recent article outlining the roadmap for sustainable design research over the next ten years specifically listed digital design tools as a necessary area of focus [77], noting that: "The long-term goal is to define evidence-based, generalizable best practices for integrating digitized sustainability data from [sustainable design tools and methods] into product life cycle management systems, to enable traceability of sustainability data…This includes tracking ecological and social responsibilities, both direct and indirect, for materials, manufacturing, transportation, usage, and end-of-life."

This suggests that digital tools are necessary to convey environmental impact data, social responsibility data, and product data to track locations, lifetimes, end-of-life outcomes, sustainable sourcing information (e.g., fair trade), and more. Each of these topics presents challenges to data gathering, visualization, and interpretation for making sustainable design decisions. A combination of these functionalities is even more challenging. Additionally, since company sustainability officers often receive little to no extra time or resources to improve sustainability, tools need to be inexpensive and easy to use [78].

Data visualization for sustainable decision-making

Another area of promise we would like to highlight for HCI research is chemical toxicity hazard assessment, used for Cradle to Cradle certification and prioritization of better materials. In particular, work is needed to make hazard data comprehensible to non-toxicologists through better data visualization, more transparently weigh hazard categories [79], and address chemical safety data gaps [80]. Machine learning and other analytics could help fill these data gaps both by reading existing literature not yet incorporated into open-access toxicity databases, and by algorithmically predicting toxicity based on molecular formulas, as tools like CompTox do [81].

Further regarding data visualization in the context of sustainable design decision-making, there is a major opportunity to explore ways to visualize uncertainty in data. Traditional scalar methods of visualizing uncertainty such as box plots and error bars are often not understood by nontechnical decision makers in business; even trained engineers who do understand them sometimes unconsciously ignore them in decision-making. While users are often most familiar with error bars, these visualizations are not always effective [75]. During the early brainstorming sessions for EcoSketch, ideas such as quantile dot plots and various animated visualizations were considered but not pursued, although they could be promising. Newer strategies such as blur charts and violin plots are increasingly being used to represent uncertainty in environmental impact data; they show promise, but need to be studied for their effectiveness and usability.

A more technical data visualization and analysis research avenue is compressing many sustainability metrics (e.g., eighteen environmental impact categories) into simple design recommendations that are actually actionable by practitioners. For example, a statistical approach to computing and visualizing uncertainty in LCA results that has gained prominence is the Stochastic Multi-Attribute Analysis (SMAA), found to be particularly effective for situations with trade-offs, making them more useful for less technical audiences and cases where environmental impacts are only some of many criteria used in decision-making, such as PD [72]. Other methods involve normalizing and weighing different impact categories into a single score, but there are several such methods. Research partnering data visualization experts with sustainability experts is required to determine such systems' accuracy, repeatability, scalability for many comparisons, display of uncertainty, clarity, ease of use, and other factors influencing effective support of decision-making in industry or policy.

Building interdisciplinary community collaborations, and systems-level thinking to address sustainability challenges

Our experiences indicate that designing and developing LCA tools, as described here, is a powerful avenue for collaboration between HCI researchers and industry practitioners. While EcoSketch has addressed many of the challenges at the intersection of HCI and LCA, it has unearthed plenty more challenges to be addressed. One salient example is supply chain transparency, which involves sharing high-quality environmental impact data among numerous supply chain stakeholders while preserving confidentiality [82].

Further, HCI can benefit sustainability work beyond just impact assessments. For example, systems thinking is critical to setting sustainability priorities and avoiding unintended consequences, but complex system maps are often difficult to generate and interact with; HCI could improve this. The sustainable design method biomimicry suggests that engineers and designers improve sustainability by imitating nature; but practitioners find it difficult to connect natural and industrial materials and processes [83]. For example, when the inventor of Velcro was inspired by burrs sticking to his dog's fur, it took him ten years to find viable materials and manufacturing methods. AskNature.org, a database of biomimicry strategies and inventions, addresses this problem and is a powerful example of a sustainability tool that incorporates HCI principles. For every tool like AskNature or EcoSketch, many more collaborations between HCI researchers and sustainability professionals have yet to be realized.

Another important avenue is enabling more collaborative forms of sustainability analysis, especially along supply chains where intellectual property prevents sharing product data but allows sharing impact data. There are several factors to a tools' potential for creating such a community; we would like to highlight three: accessibility, explorability, and shareability. Tools that are more accessible, particularly for audiences with less scientific computing and statistical background, allow more users with a greater variety of skill sets to come together around the data. Tools which are highly explorable let users move through the analysis at their own pace, in their own way, and based on their own curiosities–often through the use of interactive visualization elements like tooltips, click-to-filter, and drill-down visualizations. Finally, shareability allows individuals and organizations to share their analyses with others. Tableau is bringing some accessibility, explorability, and shareability to business contexts: it's designed to be accessible to less technical users, it has lots of interactive visualizations, and by being a web-based platform it has made sharing relatively easy. Further research is needed into how we might create tools that are accessible but still rigorous, into the effectiveness of various forms of interactivity visualizations for making data explorable, and into ways to make data and analysis shareable within the sustainability data landscape, especially large-scale data from entire industries, in which much of the data is proprietary.

2.3.6 Design Implications

In this section, we first reflect on design implications and opportunities for improvement based on insights from our development and evaluation of EcoSketch. Feedback from our interviews pointed to a variety of improvements to the design of lightweight LCA tools like EcoSketch. These features address the aspects found to be of critical importance to our target users: enhanced flexibility of use, learnability, the ability to account for uncertainty, visualizing results for easy sensemaking by novice users, and error recovery. To support further flexibility of use, we identified an opportunity to allow users to duplicate parts and sub-assemblies in the model as well as to input more granular uncertainty data instead of the predefined levels (low, medium, and high). To enhance learnability, users expressed a desire for tooltips with help-text for key features. Creating a built-in tutorial that walks users through creating their first LCA model and analyzing results is also worthwhile, as we saw that users benefitted from this sort of tutorial that we prepared as part of the experimental procedure. To account for uncertainty, tools can incorporate additional and novel methods of viewing uncertainty such as Stochastic Multi-Attribute Analysis. In addition, we see continued innovation regarding effective use of color and representation of uncertainty in visualizations as important avenues in easing the sensemaking of results.

Regarding error recovery and quality assurance, EcoSketch could add up the masses of all the parts in a given sub-assembly and for the overall assembly on the model-making canvas, allowing users to make sure their inputs were accurate, and that they are not missing any parts in the model. Further, we identified utility in allowing users to trace errors from the visualization page to the exact part or sub-assembly in the model-making canvas. Trace precedence more generally refers to features that could allow users to select a part of the results graph that they would like to review the inputs for . Finally, we see great value in offering users the ability to track and manage changes to their models. As tools like EcoSketch help realize our vision of lightweight LCA processes that become more iterative, version control options are a natural feature so that users can track environmental assessment changes as the project progresses throughout the PD process.

2.4 Study limitations and future steps

Our evaluation of EcoSketch revealed several opportunities for improvement, but also confirmed the quick learnability and improved efficiency of our approach, in large part due to its support for uncertainty and under-specification during environmental assessment processes. Results showed how a complicated quantitative assessment technique typically limited to experts can be made accessible to novice users seeking to rapidly integrate a new practice into a design workflow.

However, while we engaged in formative needfinding in close collaboration with industry practitioners, a majority of the participants in our study were undergraduate and graduate engineering students as a more feasible proxy population. Students were screened for representativeness of this target professional group based on their experience working on product design projects through classes, internships, or personal projects. Another limitation of the lab-based setting is that the experimental task could only last a constrained session of time. However, we plan to conduct this experiment with a larger sample size to improve robustness of the data. Moving forward, a natural next step is therefore testing with actual industry practitioners in professional settings over longitudinal periods, now that the fundamental merit of EcoSketch's approach has been validated and can be further refined for such real-world evaluation. As always, there is more work to do. In conducting such studies to validate the efficacy of tools like EcoSketch in informing actual decision-making processes for product designers, it is also worth investigating how earlier-stage insights actually integrate into corporate sustainability efforts and decisions. Further, it is important to perform comparisons between lightweight and heavyweight LCA tools and between expert and novice users to examine the nature of the design decisions that emerge and the resulting impacts with respect to different types of PD practices, products, and organizations. Finally, and broadly, it is important for our interdisciplinary research communities to continue forging strong and lasting partnerships, such as our collaborations with Synapse and EarthShift, which will enable deeper study of the ways in which digital tools can support sustainable decision-making in industries.

In concluding this chapter, we revisit the the two main challenges presented by the ecodesign paradox in Chapter 1:

1. Practitioners face barriers in quantifying the environmental impacts of their design decisions early-on in the PD process.
2. Practitioners face barriers in translating the environmental impact results generated by LCA tools into actionable design decisions.

This chapter focused on the challenges presented by existing LCA tools, as well as an extensive design and development process to create EcoSketch, an LCA tool tailored for use by novices in the early-stage PD context. In the next chapter, we tackle Challenge #2 by addressing how LCA results on environmental impacts can be translated into actionable design decisions through modular, reusable, and systematic frameworks.

Chapter 3. Co-creating and integrating sustainable design into product development at a consultancy: Synapse Case Study

As part of this case study, I explore the considerations that influence the integration of sustainable design strategies into real-world PD practice. During my time as an intern at Synapse, I realized that simply having access to human-centered LCA tools to quantify environmental impacts was not enough. Practitioners often struggled to identify appropriate sustainable design strategies to address the impacts identified through LCA. Lack of training in sustainability coupled with the existence of a massive variety of sustainable design methods and tools (SDMTs) further complicate matters.

This chapter and the next chapter aim to a) more deeply understand how sustainable design integration plays out in practice, (b) surface barriers and enablers to the integration, and (c) collaboratively develop a flexible framework that supports the translation of sustainable design practices into a real-world PD setting. Taking a human-centered approach to the co-creation of these practices places my partner organizations' (Synapse, here) context and needs at the heart of the research. Specifically, I was embedded at the firm as an intern to understand the intricacies of Synapse' PD practice through ethnographic observations, interviews, focus group sessions, and tailored activities to co-create their sustainable design process.

The development of the framework aims to support a structured yet flexible data-driven approach to sustainable design decision-making. Specifically, it guides the iterative selection of sustainable design strategies in the PD process using results from LCAs, and client priorities. Key contributions of this chapter include:

- Iterative, human-centered, and collaborative co-creation process of a sustainable design framework tailored to the employees' needs and PD context;
- A set of qualitative considerations, identified through extensive user research, that influence the adoption of sustainable design;
- A co-created, modular framework of practices that satisfies these considerations and aids the systematic integration of sustainable design into PD workflows;
- Insights and feedback related to the framework's deployment in practice obtained through longitudinal engagement.

I devised the following research questions (RQs) to guide our observation, interviews, and co-creation of the sustainable design framework with Synapse:

- **RQ1 – Receptivity to integration:** What factors drive the company's receptivity to incorporating various SDMTs into their PD practice?
- **RQ2 – Valued tools:** What do practitioners value in existing SDMTs?
- **RQ3 – Co-creation:** How does the process of co-creating a customized sustainable design framework enable its integration into the company's PD practice?
- **RQ4 – Long-term impacts:** How does the framework support continued consideration of sustainability in the company's PD practice over time — or if it fails to do so, why?

With these RQs in mind, Section 3.1 presents the methods employed to engage with Synapse. Section 3.2 discusses insights from interviews, focus groups, and other captured data, with findings organized by emergent themes around incorporating sustainable design into PD. Section 3.3 discusses how these insights were collaboratively translated into a modular sustainable design framework, and revisits how this work answers our guiding RQs. I conclude with how the firm continues to employ the framework, and future research opportunities unlocked.

3.1 Materials and Methods

3.1.1 Participants and Study Materials

The industry partner selected for this case study was Synapse Product Development Inc. (referred as "Synapse"), an engineering/design consultancy specializing in consumer electronics applications. We chose them for several reasons. First, literature suggests that PD consultancies often lag manufacturing firms in terms of sustainability expertise [84], [85] and therefore face a greater unmet need to integrate sustainability into their practice. Second, as an engineering consultancy, Synapse employees were comfortable working with both qualitative and quantitative methods, which enabled a variety of mixed methodologies to be on the table during the co-creation process. Third, Synapse employees were very receptive to my research, owing to a growing interest in sustainable products among their clients, representative of a larger trend in the industry. In addition, Synapse and their clients struggled to identify the right SDMTs for their application, from the numerous alternatives published in literature. Finally, Synapse had some familiarity but no deep expertise in sustainability, making them a representative case as far as how the introduction and integration of a sustainable design framework unfolds in real practice. This combination of factors made them an excellent case study for this research into how to effectively integrate SDMTs into PD practice.

Synapse has close to 150 employees in these main divisions: mechanical engineering, electrical engineering, firmware engineering, new product introduction (NPI), project management, and a senior leadership team constituting the heads of all divisions. Project teams typically consist of 8-25 employees spanning across divisions. Project timelines range from six months to two years, based on the scope. Some clients require Synapse's support throughout the PD process, while others require them to contribute to just a specific stage of PD.

I worked with Synapse as a mechanical engineering intern for a period of four months and participated in the day-to-day PD workflow of the company. This enhanced the iterative design and testing of the sustainable design framework before arriving at the final version presented in this paper. In total, I interacted with 25 employees spanning across divisions, of whom 10 were particularly active in contributing insights. These participants (3 female, 7 male) had work experience ranging from 4-21 years. Table A1 in the Appendix provides their full characteristics and anonymized identifiers.

3.1.2 Data Collection

I worked alongside these participants to observe and understand their day-to-day PD workflow and what the integration of sustainability considerations meant for their practice. This was the central theme for most early interviews and group discussions, with insights speaking largely to RQ1 and RQ2. Later sessions involved presenting variations of the framework to gather feedback and iteratively make refinements. By being embedded at the firm as an intern, I established rapport and trust with my colleagues so they could comfortably share both positive and negative feedback.

Interviews and focus groups

I conducted a total of 17 group discussions and four one-on-one semi-structured interviews with Synapse employees. Each session lasted an average of 45 minutes. Audio was recorded for transcription and analysis. In group discussions where recording was not possible, I made detailed notes including quotes of participants' comments.

Interviews explored questions about what incorporating sustainability within Synapse's PD practice meant to the employees in their different roles and divisions. P1 (firmware engineer), P2 (electrical engineer), P3 (NPI), and P5 (project manager) participated in 1:1 interviews. The 1:1 format allowed a deeper dive into what individuals valued or did not value about various aspects of the framework.

Group discussions involved presenting participants with versions of the framework and lists of relevant strategies identified from various methods and tools for feedback. Discussions centered around specific aspects of the framework structure, what strategies from different SDMTs employees valued and why, and how the framework could be designed so as to be readily incorporated into the Synapse workflow. I moderated the discussions by asking questions and taking notes. Group sessions allowed the participants to exchange ideas and build off of each other's arguments, highlighting instances of agreement and disagreement. Participants P4 and P6-P10 attended several discussions and actively contributed insights. Their roles spanned senior leadership, strategy consultants, and engineers.

Reviewing Project Documentation

As part of my investigation into Synapse's PD practice, I obtained access to documentation on past and current projects to better understand the company's PDP conventions and project workflows. I looked specifically at project timelines, milestones, frequency of client interactions, distribution of roles and responsibilities, and decision-making processes which altogether helped guide the creation of the framework.

Participatory Development of the Sustainable Design Framework

I took an HCD approach to co-create a framework putting users' needs first and paying particular attention to making the framework useful and usable. We arrived at the final framework through closely observing the PD workflow across various projects, conducting interviews and group discussions with a wide range of practitioners, and iteratively designing and testing various potential interventions. User participation helps provide deep insight into their needs, and enhances the acceptance of the outcome, which I observed over the course of the longitudinal engagement following the initial study. The participatory, collaborative, and iterative process is depicted in Figure 19.

Ongoing engagement with the company post-internship

I continued to engage closely with Synapse following the conclusion of my internship. Specifically, through a total of 55 weekly follow-up Zoom sessions amounting to 28 hours of discussions over an additional year, we gathered feedback from teams that adopted the framework to learn how it could be further improved and made notes of key insights. Notes from these sessions were thematically analyzed, as described in Sec 3.1.3, similar to the interview transcripts obtained earlier. During this longitudinal phase, we learned how the framework had since been applied to varying extents in four different projects, the most recent of which stemmed from a client reading a white paper that Synapse published about the framework.

3.1.3 Qualitative data analysis

Interview transcripts and group discussion notes were qualitatively coded to identify patterns and extract insights [68]. The emergent themes describe key considerations we sought to address in the co-creation process. Table 5 in the Results section summarizes these high-level themes, together with sub-themes that reflect specific considerations.

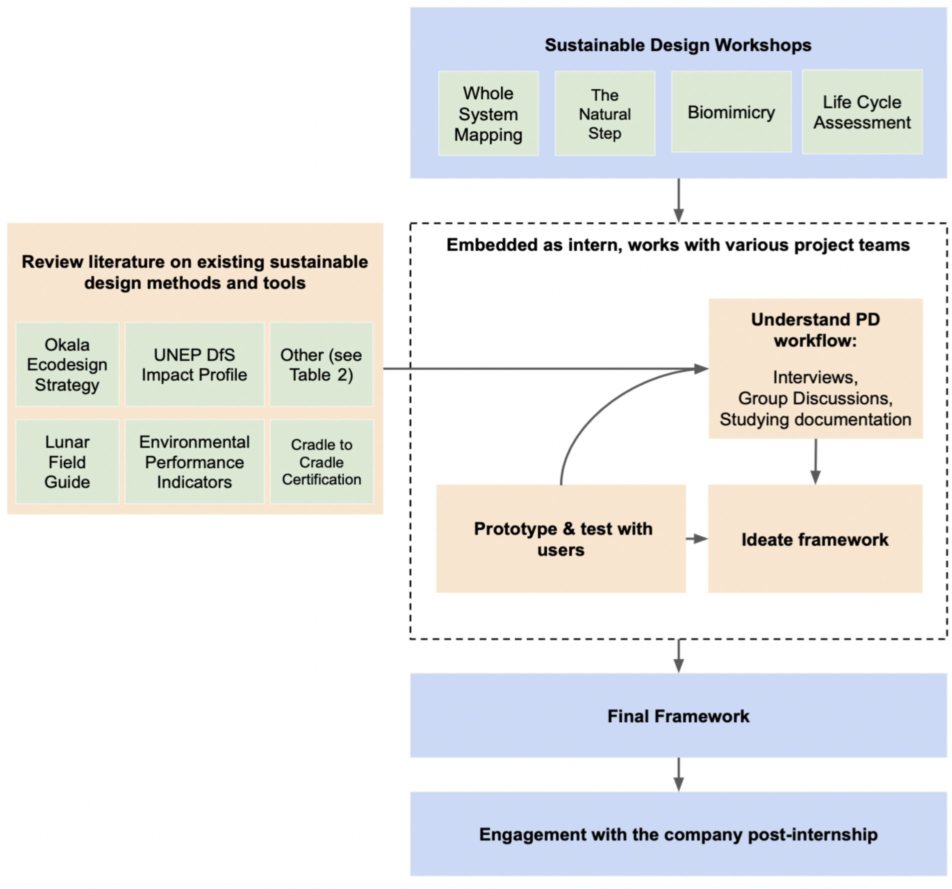

Figure 19: The iterative, participatory process applied to co-create the sustainable design framework and answer research questions

3.2 Results

Thematic analysis of the qualitative data collected lead us to identifying various themes and sub-themes critical to answering the research questions surrounding: i) what drives receptivity towards incorporating SDMTs at a company, ii) what SDMTs employees at this company valued and why, iii) insights gained from participatory co-creation of the framework, and iv) long-term impacts. Sections 3.2.1, 3.2.2, 3.2.3, and 3.2.4 unpack the insights from the themes, organized by the research questions they address.

Table 5: Themes and sub-themes extracted from the qualitative analysis of interview and focus group transcripts and notes

Research Question	Themes	Sub-themes
RQ1: Receptivity to integration	Relationships with clients/stakeholders	Supporting the clients' decision-making on trade-offs against cost, performance etc.
		Communicating the value of sustainability
	Discipline-specific insights	Manufacturing Engineering
		Program Management
		Firmware and Software Engineering
		Electrical Engineering
		Mechanical Engineering
		Senior Leadership
RQ2: Tools valued	Structure of the framework (design strategy repository)	Sustainability focus areas & TBL
		Sustainable design strategies & focus areas to triple bottom line
		Sustainable design strategies & LC stages
		Sustainable design strategies & PD phases
RQ3: Co-creation	Integrating the framework into the firm's workflow	Defining what sustainable design means to all Synapse employees
		Making sustainability a part of the culture
		Ownership or responsibility for sustainability concerns on projects
		Access to resources for learning
		Making internally generated resources accessible and easy to use
		Improving visualization and communication of LCA results
		Supporting the internal decision-making on trade-offs against cost, performance etc.
RQ4: Long-term impacts	Applying the framework in practice	Measure: Using LCA to identify hotspots
		Identify: Identifying relevant strategies in the repository
		Apply: Applying the identified strategies to improve environmental performance

3.2.1 RQ1: What factors drive receptivity to incorporating SDMTs into PD practice

The first research question addresses what factors facilitated or hindered the firm's receptivity to incorporating SDMTs into their PD workflow. The following subsections describe three key themes that emerged as indicators of receptivity: 1) organizational culture, 2) relationship with the client, and 3) the need to appeal to employees from different disciplines differently. I use participant quotes to contextualize my observations, demonstrating how the framework was grounded in participant input. This section helps provide a rich picture of the soft side of sustainable design implementation.

Integrating sustainability into company culture

During my interviews, Synapse employees emphasized the need to integrate sustainability not just into their PD workflow but also into their organizational culture. P8 indicated that discussions within teams and with clients needed to include sustainability indicators alongside cost and engineering performance, to emphasize *"sustainability and social impact as something that [Synapse] is integrating into our DNA"*. This sentiment around responsible innovation was echoed by other participants, including P1 who expressed a desire for Synapse to also *"focus on social and ethical considerations"*.

We started by trying to define what sustainable design meant for Synapse, both to eliminate ambiguity and build ownership and commitment. Upon brainstorming several versions with senior leadership and getting feedback from other employees, we landed on: *"sustainable design at Synapse focuses on maximizing environmental, social, and economic benefits over a system's life cycle, while minimizing associated social and environmental costs"*. Following agreement across the board, several questions arose including: *"who owns the sustainability aspects of the project?"*, *"how do we define the* *metrics for success"*, *"when do we know we are done?"*, and *"can we track sustainability metrics the way we track cost?"* Participants felt that the project managers (PMs) should track sustainability tasks and metrics as they track engineering tasks and metrics. PMs were found to be a key stakeholder in sustainability integration because they form the interface between the client and the engineers, translating client needs into requirements.

Despite Synapse' dedication to incorporating sustainability into their PDP, the firm is somewhat limited as a consultancy, wherein they can only make recommendations that must ultimately be approved by their clients. However, P6 expressed optimism that *"as more companies commit to sustainability targets, this would start to be the norm and not the exception"*, a sentiment core to the incorporation of the framework in practice.

Relationships with clients and stakeholders

Building on this theme, my interviews further explored where sustainability fits in the client-consultant negotiations, and how client buy-in can be critical for integration.

Interviews identified the delicacy of communicating the value of sustainable design to their clients. P5, a PM who is often the interface between a PD team and the client, said, *"they come to consultancies like Synapse because they need engineering support… it is easy for [Synapse] to sell them on the immediate value of engineering services but might not be easy to sell on the value of going through this [sustainable design] exercise"*. This was especially true for clients who had not set sustainability targets. Furthermore, adopting sustainable design practices inevitably adds time, which can be seen as a drawback by clients because they are paying for consulting services by the hour. P5 indicated that clients were typically looking for the *"best bang for their buck"*, and sustainability may not always be their priority. Thus, to accelerate adoption, participants perceived value in minimizing time spent on sustainable design.

P5 described client satisfaction as the *"delta between what they get and what they expect"*. These insights emphasize the importance of predictably delivering on expectations in order to build a strong long-term relationship with the client. We identified the need for transparency and accuracy with estimating the time and other resources required, leading us to label strategies in terms of *"low", "medium", or "high"* effort. Such estimation could eliminate process uncertainties, both for clients and employees, potentially improving receptivity. Identifying low versus high effort strategies also helps trade off operational cost-benefit.

P5 reminded us that Synapse deals with a *"wide range of clients; some really care about [sustainability], while others have it way down low on their priority list"*. He said it was important to get the fundamental message across *"without getting stuck in the weeds"*. P7 added that *"sustainability was previously perceived as being at the expense of profitability, but recent models have shown that actually, sustainable business models are better in many cases."* Case studies can be an effective way to convey the value of considering sustainability in PD practice, an approach currently employed by Synapse's New Product Introduction (NPI) team to promote design-for-manufacturability. This highlights how finding ways to better communicate the value of sustainable design, such as with the use of case studies, leads to receptivity and long-term integration of strategies. We also recognized the importance of understanding the factors motivating a client's receptivity to sustainability, and therefore the SDMTs they value, addressing tools valued in conjunction with integration. P9, a strategy consultant, explained that *"a client's* *sustainability needs are often either regulation-driven or market-driven"* and that she was seeing *"FMCG [Fast-Moving Consumer Goods] companies in the EU focusing on minimizing plastic use, driven by stricter regulations"*. Organizing sustainable design strategies/methods in the Synapse repository according to the UNEP Design for Sustainability Guide's focus areas (listed in Section 3.2.2) provides Synapse employees a structured format to explore where the biggest environmental benefits lie and help clients set or modify their sustainability priorities. It also allows their clients to market their product as having specific benefits over their competitors. The focus areas support constructive engagement with the client on environmental impacts in vocabulary familiar to them, potentially enabling buy-in.

We recommended that these conversations start in the early project-scoping stages, followed by periodic check-ins where sustainability performance is reviewed alongside other engineering performance indicators. P7 agreed that it was important to *"get clients involved as early as possible, because that's when we can have the biggest impact"*. This approach enables Synapse to: help clients set appropriate high-level sustainability goals, set relevant objectives for the project, and track key performance indicators.

Discipline-specific insights

Conversations with a diverse range of participants showed that their receptivity and perspectives on sustainability were uniquely shaped by their roles and disciplines at Synapse. For instance, project managers (PMs) at Synapse have the most interaction with the clients, while also managing the project scoping, timelines, and workflow. P5, who was a PM, agreed that it was his job to identify the *"areas to focus on throughout the product design process"* largely through periodic conversations with the client. He expressed that it was also his purview to *"minimize the overhead time that it takes to do [LCA] in terms of using lightweight tools"*. He was keen on optimizing the sustainable product design process, asking, *"How do we have the biggest impact with the least time and resources?"* As discussed further in 3.2.2, this led us to prioritize the use of simplified (lightweight) LCA tools for periodic assessments, enhancing their integration in both the short and long terms.

The NPI engineer (P3) oversaw the firm's design-for-manufacturability efforts and could empathize with the difficulty in communicating the value of incorporating sustainability early in the PDP. He said, *"NPI engineers work hard to convince clients of the value of including a manufacturing engineer on the team early-on"*. To overcome this, he said they often point to case studies when a prototype was deemed *"not manufacturable"* too late in the process, adding to tremendous costs that could have been avoided. To improve both receptivity and long-term adoption, we also recommended compiling such case studies to more tangibly demonstrate to clients the value of sustainable design.

P1, a firmware engineer, did not think that incorporating sustainable design would affect his workflow much, as he saw it as *"mechanical, electrical, and NPI heavy"*. He added that their division was typically *"not involved in the early product design decisions"*.

Interestingly, he pointed out that they already followed practices that *could be considered sustainable*, such as *"maximizing battery life, reducing power consumption, seeking tier-1 chip manufacturers, and future proofing by using technology that might not become obsolete in the near future"*. He clarified that such strategies were motivated by economic considerations. This helped us recognize how professionals can appreciate and adopt sustainable practices for their economic and engineering performance benefits.

3.2.2 RQ2: What do practitioners value in existing SDMTs?

The second research question addresses what SDMTs employees at Synapse valued or did not value, and why. The following subsections describe how this led to: 1) the compilation of a list of SDMTS valuable to Synapse's context, and 2) how these SDMTs were organized into a framework to support their selection and application.

Compiling relevant strategies

This involved compiling a list of sustainable design strategies which were individual activities, mindsets, or a combination thereof as strategies, from existing SDMTs in literature. This approach was based on the idea that *"multi-step methods are often not applied as tunnels of process in practice"* [22]. Synapse employees confirmed that they often used parts of methods as opposed to applying whole methods as prescribed.

Table 6 depicts the methods and tools considered and/or selected to be included in our compiled list of strategies. We ensured that they addressed all three pillars of sustainability (environmental, social, and economic), and spanned a diverse range of methods (qualitative, semi-quantitative, and quantitative). Decisions to include a certain strategy in the final list were made through discussions on what strategies were found valuable or not valuable, and why, as specified in the table.

Table 6: SDMTs considered and/or selected to be included in the framework

Methods considered	Env	Soc.	Ecn.	What were these methods valued for?
Integrated as framework structure:				
Whole System Mapping (WSM)	X	X	X	*"systems-level view", "data-driven"*
Simplified Life Cycle Assessment	X			*"quantitative rigor"*
UNEP Design for Sustainability	X	X		*"easy-to-understand categorization"*
Checklist for Sustainable Product	X	X	X	*"comprehensive", "developed in an industry context…might be more*

Development				*relevant than academic tools"*
Strategies selected:				
Okala Ecodesign Strategy Wheel	X			*"selection of strategies by life cycle stage"*
The LiDS Wheel	X			*"selection of strategies by life cycle stage"*
Cradle to Cradle Certification	X			*"clearly defined requirements", "reputable industry standard"*
MET Matrix	X			*"toxicity of materials and processes"*
Design for remanufacturing	X		X	*"strategy relevant to sustainability"*
Design for recyclability	X			*"strategy relevant to sustainability"*
Design for disassembly	X			*"strategy relevant to sustainability"*
Design for serviceability	X		X	*"strategy relevant to sustainability"*
Considered as optional tools:				
Product-related Environmental Performance Indicators	X			*"Great resource for metrics!"*
Factor 10 Engineering	X		X	*"Relevant but obvious"*
Product Service System Business Model Landscape	X	X	X	*"Often outside our scope [of influence]"*
Circular Design Guide	X	X	X	*"Some useful methods and tools"*
12 Leverage Points	X	X	X	*"High-level", "useful for early-stage client negotiations"*
Not used:				
10 Golden Rules for Ecodesign	X			*"Already considered these strategies"*
Supplier Social Sustainability Indicators: Emerging Countries		X		*"Often outside our scope [of influence]"*
Ecodesign Maturity Model	X			*"Useful for management consultants"*
Ecodesign Checklist Method	X			*"Repetitive"*

We discussed the individual activities/mindsets within each of the methods described in Table 2 with participants P4, P6, and P10, and narrowed down the list to the final version presented in Figure 23. Several strategies were eliminated based on repetition/overlap with those in other methods listed prior. Further, many strategies were not valued because they were not within Synapse's typical scope of influence on a project as expressed by P10: *"Synapse typically has the biggest impact on material selection and product design; packaging/distribution are rarely something we can influence"*. Such perceptions around scope of influence heavily impacted what strategies participants valued.

Foundation for the framework structure

We now created a framework structure that allows users to select the right sustainable design strategy for the job iteratively through a project. Our framework starts with an early-stage "Innovate" step that encourages users to explore and brainstorm interventions at the system-level. As the product/system idea is solidified, users are encouraged to perform a quick simplified-LCA to identify hotspots by life cycle stage, allowing users to target the sources of biggest impact. Users perform the steps: "measure impacts", "identify hotspots", and "apply relevant strategies" iteratively throughout the PD process. Incrementally, the uncertainties associated with performing LCA early-on shrink over time. The existing Synapse PDP follows a stage-gate process of the following stages: 1) Discover, 2) Define, 3) Evolve, 4) Develop, 5) Realize, and 6) Support, as shown in Fig 20. We observed that while there was an emphasis on iteration between phases, there was also a fast-paced progression through the phases in order to meet tight timelines.

The value of iteratively applying the process and tracking indicators over time was articulated well by P8: *"Most of these strategies need to be implemented in a periodic fashion. Materials/processes may change later, and we would still need to review if, for instance, they are conflict minerals or pose health risks."*

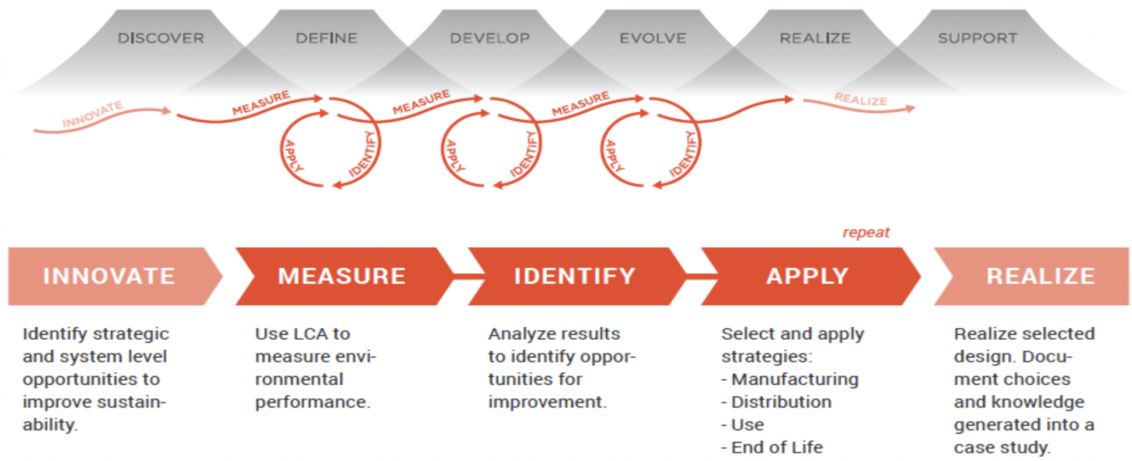

Figure 20: The framework's sustainable design stages (in red) are applied in parallel to the PD process (in gray)

Overall, the iterative nature of our framework's sustainable design process goes hand-in-hand with an iterative PD process, thereby enhancing the integration of the activities. P5 and P6 suggested tracking and visualizing sustainability KPIs alongside cost and other engineering KPIs: *"can we track environmental impacts in the same way that cost is tracked as design is refined?"* P6 further suggested *"tracking the narrowing of uncertainty in LCA BOM input"*. Participants desired to periodically track KPIs during the PD process, including when negotiating tradeoffs with clients.

3.2.3 RQ3: How does co-creating a framework with employees enable long-term impact?

In this section we discuss the advantages of collaboratively creating the framework with our industry partners. The development of the framework underwent several iterations based on periodic feedback obtained through observation, interviews, and discussions to align it effectively with the firm's iterative PD workflow, as summarized in Fig 21.

Subsequent subsections highlight key insights regarding the usability of the framework identified through the co-creation process: 1) better aiding selection of strategies, and 2) including early-stage system level innovation. These considerations emerged from the collaborative design of the framework.

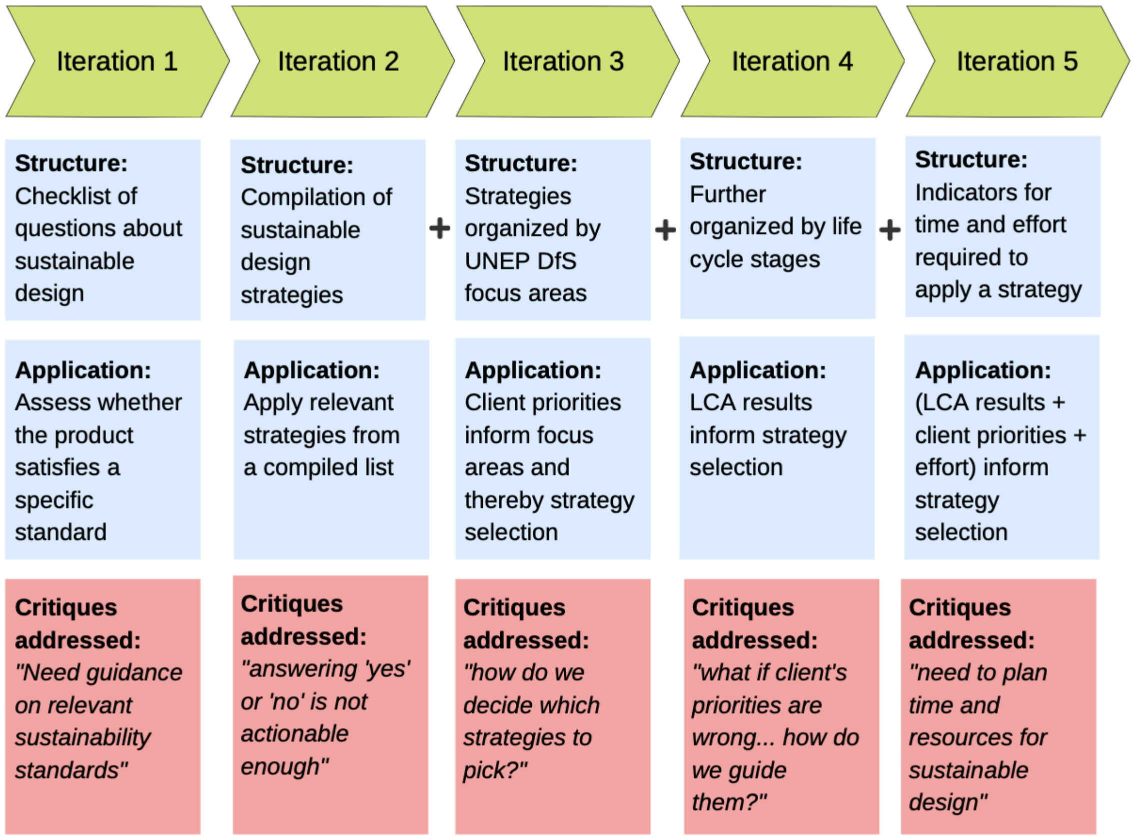

Figure 21: Iterative development of the sustainable design framework

Organizing strategies by life cycle stage, PD phase, and focus areas to aid selection

A critical insight from participant observation was that users were looking for a structured decision support framework to help with selecting the right strategies. Our co-creation focused on what levers we could provide to enable easy, logical, and reproducible decision-making. This led to discussing how to organize and tag the final list of compiled strategies selected from existing SDMTs. This list is not exhaustive and is expected to grow as the framework is used. Nonetheless, we ensured that the strategies addressed the nine sustainability focus areas similar to those used by [86], including: 1) resource efficiency, 2) resource consumption, 3) selection of low-impact materials, 4) optimizing end-of-life, 5) lowering negative environmental impacts from waste, 6) transportation and logistics, 7) health and safety, 8) social and ethical considerations, and 9) economic efficiency and profitability; these were based mainly on the UNEP Design for Sustainability impact profile [86]. We found that these focus areas could be correlated to the triple bottom line: the environmental, social, and economic pillars of sustainability, as illustrated in Figure 22. Table A2 in the Appendix includes the grouping of strategies by these focus areas.

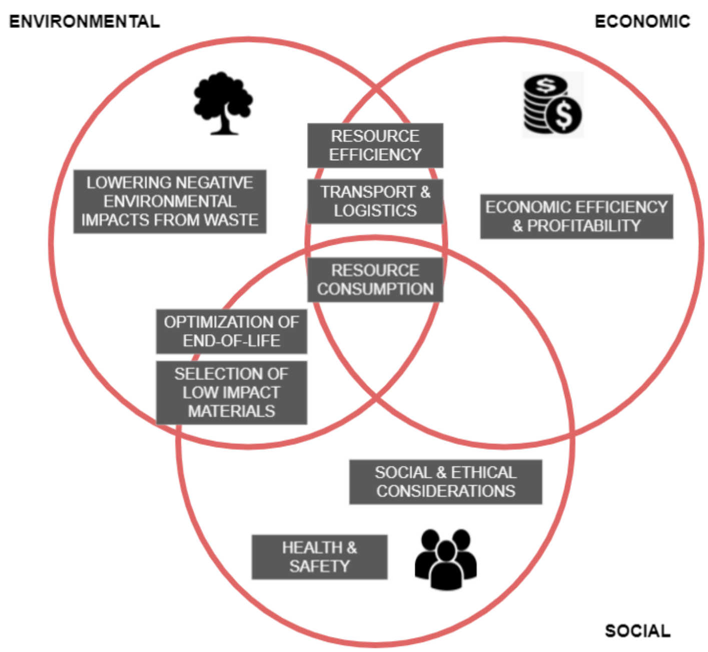

Figure 22: Connecting the sustainability focus areas to the triple bottom line to address all three pillars of sustainability

Sorting the strategies by the sustainability focus areas allowed users to narrow down to relevant strategies based on the client's priorities. This approach during co-creation helped us ensure that the compiled strategies addressed environmental, economic, and social aspects — a priority for Synapse employees, as discussed in 3.2.2. The strategies were then organized by the life cycle stages (materials & manufacturing, distribution, use, and end-of-life) to which they best apply, allowing users to select strategies based on the life cycle stages that contributed to the most environmental impacts (based on LCA results). We further linked strategies to the PD phases when they apply. For example, the strategy *"avoid conflict minerals"* best applies to the materials & manufacturing stage of the product's life cycle, in the *"discover"* and *"define"* phases of the PD process. Fig 23 details the correlation of the strategies to the life cycle stages, PD phases, and the triple bottom line. Offering multiple levers to simplify the identification of relevant strategies was found to be valued both empirically and in literature, to enhance the integration.

The framework document included additional information for each strategy for reference, based on what kind of information participants found valuable. For instance, P8 suggested including *"knowledge gap questions"*, P5 suggested including *"estimated time to apply strategy"*, and others asked for *"links to external references"*. P10 responded to an initial version with, *"it is too dry - could use more images"*, while P5 asked for *"cheat sheets"* that would help him quickly glean relevant information. P10 wanted us to include *"case studies and real-world examples"*. We included most of these content suggestions to better support the framework's overall adoption, as shown in Figure 24. The content is expected to grow as more teams learn and apply the strategies.

Participants described the iterative nature of PD, and the need to periodically discuss decisions and considerations with clients. This led us to use an iterative four-step process that is repeated throughout the PDP. The early stage **"Innovate"** step involves users initiating discussions about sustainability priorities during early scoping conversations with clients. This helps identify specific sustainability focus areas, offering a lever to narrow down to relevant strategies. If the client does not have pre-existing sustainability priorities, the focus areas offer a structure for discussion.

Figure 23: Final list of strategies comprising of activities and mindsets from existing SDMTs found to be valuable and relevant by practitioners at Synapse

The **"Innovate"** step recommends the optional use of system-level methods and tools such as: the 12 Leverage Points, System Mapping, and the Circular Design Guide to explore system-level innovation before a product/system idea is pursued. Once a product/system idea is solidified, following concept generation, the framework next scaffolds users to start to **"measure"** the environmental impacts of concepts using simplified LCA tools. These assessments lead to **"identify"** life cycle stage(s) that contribute to the most environmental impacts. This information helps practitioners select appropriate strategies to **"apply"** based on the life cycle stage, sustainability focus areas, and the PDP phase.

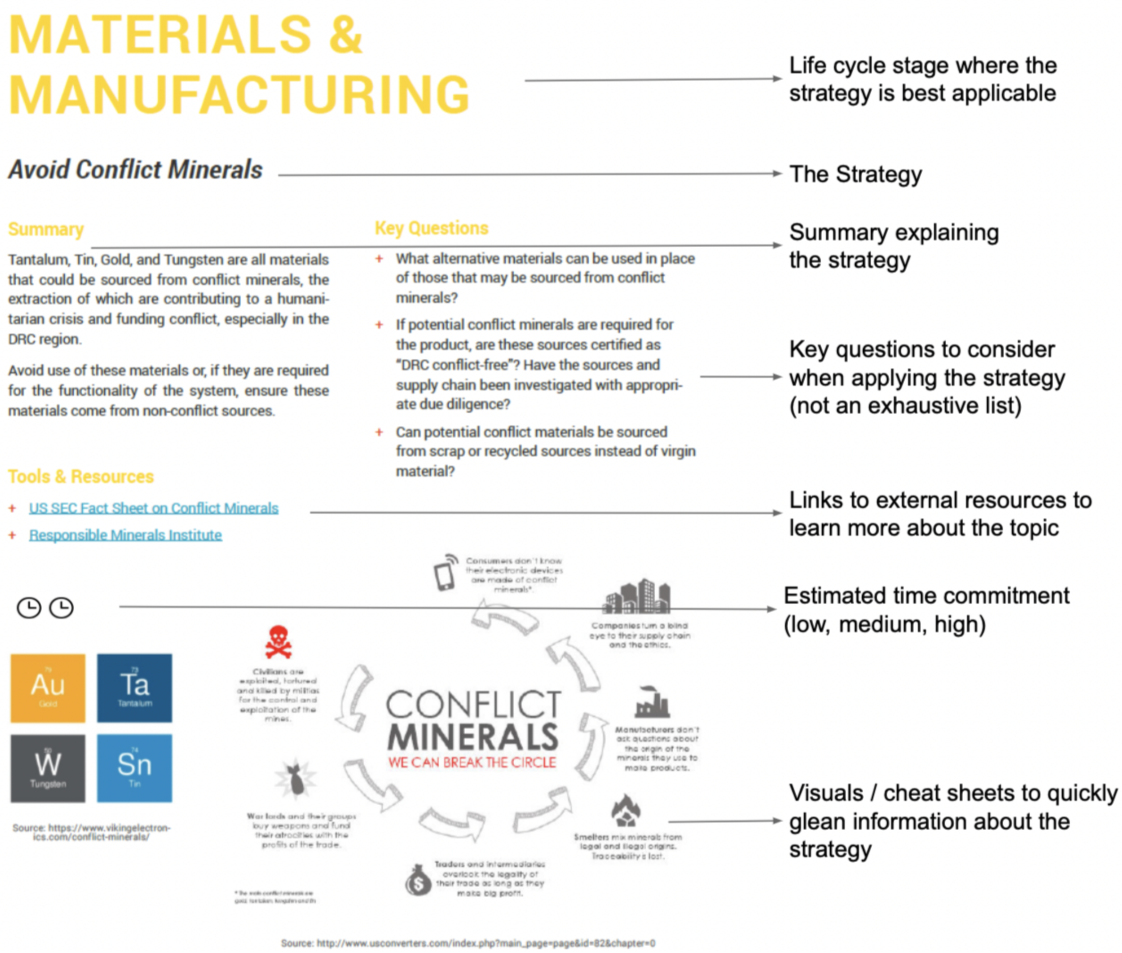

Figure 24: Summary page for strategies provides information to support its application

For instance, if the user identifies that the materials & manufacturing stage of the product contributes to the most impact, they would narrow down to strategies corresponding to that particular life cycle stage that also best apply to the PD phase they are in. Figure 25 details the overall process flowchart illustrating the iterative measure-identify-apply steps applied in parallel with the PD process. Measuring impacts provides the quantitative basis for selecting strategies that would maximize a product's environmental performance. The inherent uncertainties associated with performing LCA early-on shrink over time as the product progresses through the PD process and the inputs to such assessments become more concrete.

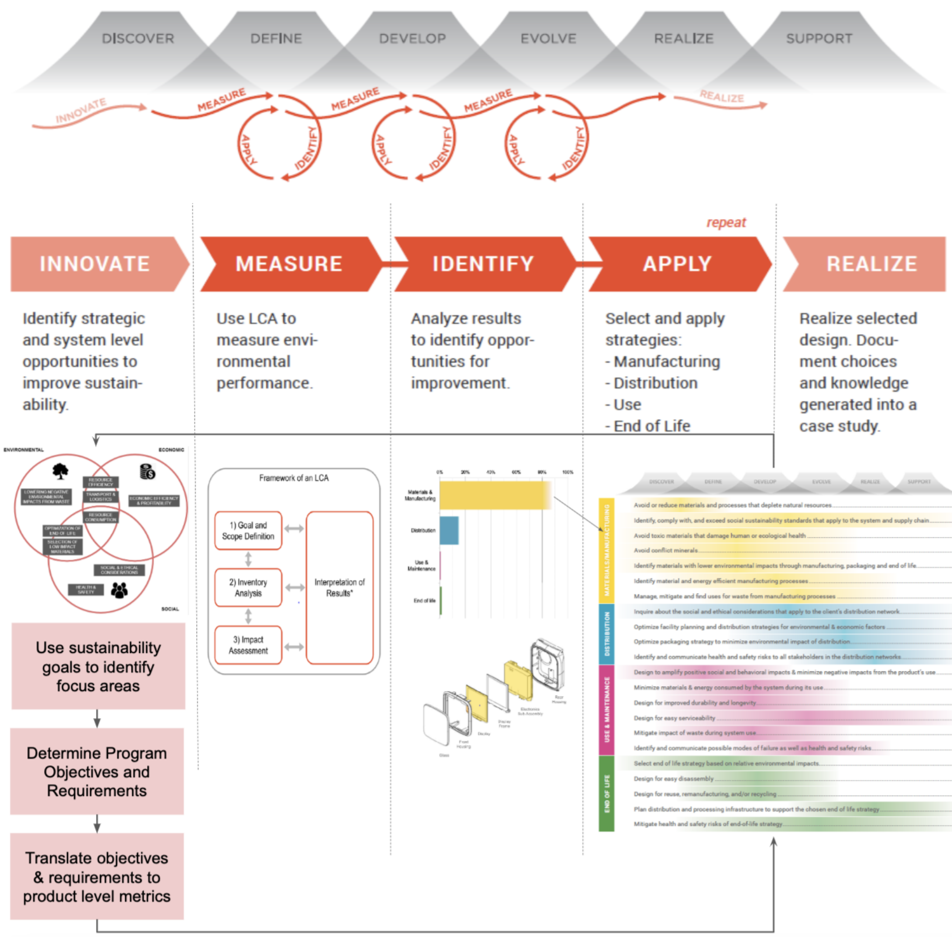

Figure 25: Flowchart detailing the sustainable design framework in PD practice

3.2.4 RQ4: How does the framework support continued consideration of sustainability?

I continued to engage closely with Synapse upon completion of my internship. Through 55 weekly follow-up Zoom sessions amounting to 28 hours of discussions over an additional year, we gathered feedback from teams that adopted the framework to learn how it could be further improved and made notes of key insights. During this longitudinal phase, we learned how the framework has since been applied to varying extents in four different projects, the most recent of which was a result of a client reading a white paper that Synapse published about the framework [87]. These projects ranged across industries, including: personal care, apparel, and home appliances, and involved the use of LCA to guide the selection of sustainable design strategies. Results showed that the products thus generated were more sustainable. Images from Synapse's marketing material (see Figure 26: a, b, & c) demonstrate the project, sustainable design methods applied, and the resulting improvement in environmental impacts.

Other insights gained from the longitudinal interaction with Synapse are below:

- Personal interest among Synapse employees has been a strong driving force for the integration of sustainable design into their PD process. Leadership support is an added boost;
- Due to the additional time and effort involved, Program Managers and Business Developers feel hesitant to pitch sustainable design to clients upfront for the fear of losing the contract;
- Limited publicity of Synapse's newly built sustainable design capabilities leads to clients not being aware of the offering in advance;
- It is yet to become a default part of every single project, with most managers waiting for clients to request sustainable design services first;

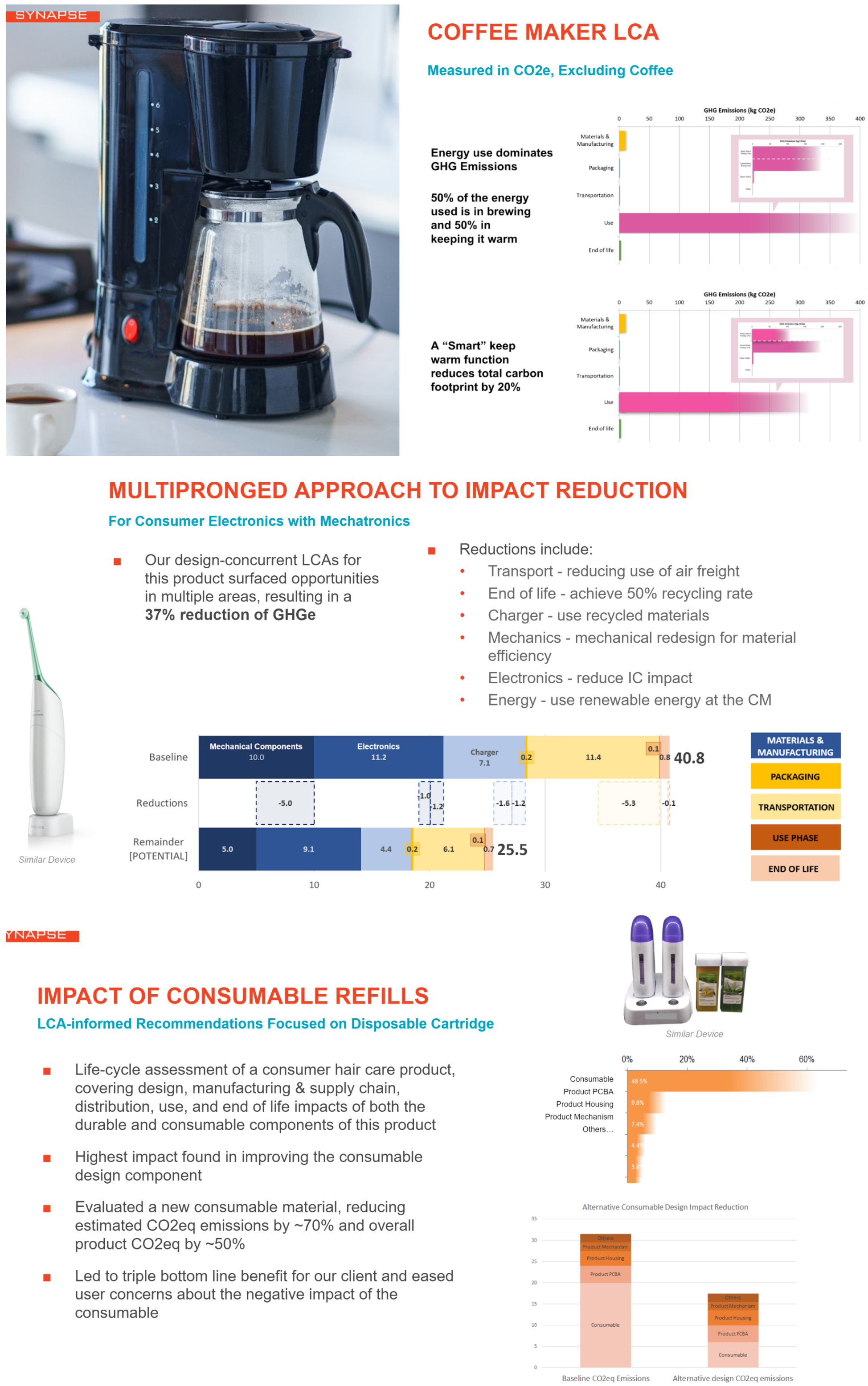

Figure 26 (a, b, c): Synapse marketing slides from three projects that applied the sustainable design framework in practice, all of which showed reductions in environmental impacts

3.3 Discussion

I have so far described the evolution of the sustainable design framework, with its components co-created in close consultation with our case study partners, and the ways it has been applied in practice, along with instances of its application with real clients over the past year. As denoted throughout the Results section, the insights discovered through interviews and discussions helped answer our research questions and informed the sustainable design framework.

My first research question aimed to understand attitudes towards integrating new sustainable practices in the first place, ***RQ1: What factors drive the company's receptivity to incorporating new SDMTs into their practice?*** Synapse employees were very open to my research and willingly took part in user interviews and discussions. They were keen for a new framework that would allow them to systematically consider sustainability in their practice. Several participants expressed a personal interest and passion for sustainability. There was also a recognition among employees and leadership that a majority of their consumer electronics products ended up in landfills. I saw this company-wide inclination towards sustainability align with a growing interest among their clients to develop more sustainable products and services.

Next I investigated perceived benefits and costs of extant sustainability practices, ***RQ2: What do professionals value in existing SDMTs?*** I found that professionals often used elements from different methods and tools, based on the problem at hand as well as the time and resource constraints faced during the PDP. Given the wide variety of existing SDMTs, they needed this support to be systematic yet adaptable in identifying the right strategy for the job throughout this process. Employees also expressed the desire to focus not on environmental, social, and economic aspects of sustainability.

I was especially interested in exploring the advantages of **collaboratively** creating the framework with our industry partners, ***RQ3: How does the process of co-creating a customized sustainable design framework better support its integration into the company's PD practice?*** Being embedded at the company as an intern allowed me to deeply understand the partner's PD process, collaboratively prototype versions of the framework, and gather detailed feedback on it through interviews and group discussions. This participatory approach improved participants' agency, buy-in, and the ultimate efficacy of the solutions produced. Our experience indicates that co-creation helped promote the application of the framework in practice upon completion of the study.

Finally I wanted to assess the framework's longitudinal impacts on PD practice, ***RQ4: How does the framework help to maintain the consideration of sustainability as part of the company's PD practice over time — or if it fails to do so, why?*** To address this question, I communicated with the company for a year after the framework was developed, learning how it had been applied on projects since. For example, their work on a recent project led them to expand upon the early stage Innovate section by including additional worksheets. The company found employing the framework to be beneficial; P6 said the framework supported a *"streamlined integration of sustainable design into their PD process"*. P4 concurred that the structured framework helped them save time.

Overall, the framework is expected to grow and change as it is applied on more projects. A broader motivation, as pointed out by participants, is for sustainable design integration to be the norm and not the exception. Synapse therefore published and widely shared white papers on this framework through panel discussion events and platforms like LinkedIn in order to: a) encourage other companies in different industries to try the approach and test its generalizability, b) attract more clients keen on developing sustainable products and services.

In conclusion, this chapter presents a sustainable design framework co-created with practitioners at Synapse to enable them to systematically apply sustainable design strategies and LCA in practice. In the next chapter, I performed a similar study at a different company, Stanley Black & Decker Inc. (SBD). These two contexts are distinct in several significant and interesting ways, including:

a. Synapse is a small engineering consulting firm with about 150 employees at the time of the study, while SBD is a large multinational manufacturing company with 70,000+ employees;
b. This study was Synapse' first foray into incorporating sustainability considerations into their PD practice, whereas SBD had a pre-existing corporate social responsibility (CSR) team who had developed methods for voluntary and mainly mandatory interventions;
c. At Synapse, teams had greater flexibility in their PD process compared to SBD.

Chapter 4 highlights how the differences in context translate to practitioners' needs for sustainable design interventions. The Synapse case study also motivated further research into whether these findings hold in a larger product manufacturer with a rigid PD process, which I conducted at SBD and describe in the next chapter. In particular, my internal comparison between business units at SBD illuminates the relationship between level of engagement in co-creation and successful long-term retention.

Chapter 4. Co-creating and integrating sustainable design into a manufacturer's product development process: SBD Case Study

In response to the ambitious climate targets set by companies across industries, there is a growing recognition to consider environmental sustainability during product design and manufacturing. With such goals being set in a top-down fashion, practitioners engaged in PD have to figure out how to adapt their practices to meet these goals. This creates a valuable opportunity for collaboration between sustainable design researchers and industry practitioners. Researchers however must first overcome any negative preconceptions and inertia to change that practitioners face. Prior work shows that educating practitioners through workshops, as well as co-creating new procedures with them improves perceptions, receptivity, and retention. In this chapter, I present my research conducted in collaboration with Stanley Black & Decker Inc. (SBD), a large manufacturer of industrial and household hardware tools, with over 70,000 employees.

4.1 Case Study Context and Research Questions

SBD is organized into two main divisions: the Industrial division which serves business clients, and the Tools division which serves end consumers. The Tools division is further divided into business units that serve both professionals and hobbyists. The Corporate Social Responsibility Division was a centralized corporate function at SBD where I worked as a product sustainability intern for two Summers: June-August, 2021 and June-August, 2022. While the company only recently published their first official environmental, social, and good governance (ESG) report in 2021, they had been pursuing and tracking progress on ambitious climate targets since 2017.

This case study explores how sustainability considerations can be systematically integrated into PD practice. I started by learning what PD practitioners valued across a wide range of existing sustainable design methods and tools (SDMTs), as well as what drives receptivity to incorporating these practices. These insights informed a highly iterative co-creation process with a team from an industrial business unit, and is compared against two other business units serving end-consumers. The comparison assesses the correlation between level of engagement in co-creation and long-term retention. As part of the longitudinal phase, I collaborated with a team to apply the newly designed sustainable design processes on a client project. Through this work, I answer the following research questions:

- RQ1: What do practitioners value in existing SDMTs?
- RQ2: Does the process of co-creating a custom sustainable design process enhance receptivity and long-term integration into practice?
- RQ3: How does a co-created sustainable design process/framework lead to the development of more sustainable products and services?

Subsequent sections detail the methods employed to answer each of these questions, followed by the results organized by the questions they answer, and a discussion of context-specific and generalizable research and business insights gleaned from this work.

4.1 Methods

This section elaborates on the research methods applied to answer each of the research questions described above. A combination of qualitative (interviews), semi-quantitative (document analysis), and quantitative (life cycle assessment) methods were employed in the process to triangulate and arrive at meaningful research insights.

The research methods followed participant recruitment, understanding drivers and barriers to receptivity, engaging in co-creation to develop a tailored sustainable design process, a longitudinal study to test integration, and finally applying the process to a project. They are organized by the methods employed to answer each research question.

To identify participating employees and teams for the duration of this project, I interviewed senior managers from each business unit at SBD that agreed to engage, including: DeWalt, Stanley Engineered Fastening (SEF), Black and Decker (BD), Stanley Healthcare, and Stanley Oil & Gas (CRC Evans).

The initial participant recruitment interview attempts to understand what it means for the business unit to incorporate sustainability PD practice, as perceived by the managers interviewed. Figure 26 represents the main aspects that were covered in this interview.

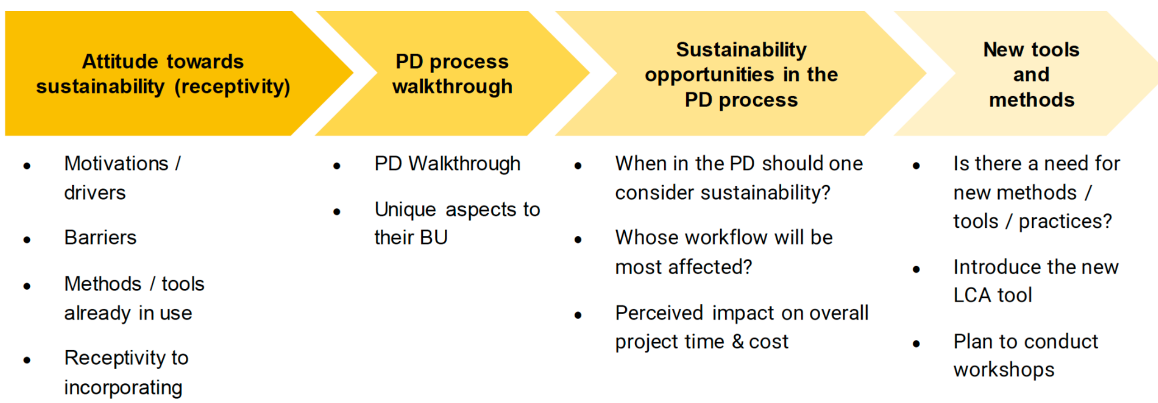

Figure 27: Template for participant recruitment interview to identify teams to collaborate with for subsequent research phases

The goal of the interview was to understand the similarities and differences in PD practices across business units, and judge their willingness to: a) collaborate on updating their practices to better incorporate sustainability considerations; and b) apply these new practices on projects real-time. Two business units that were significantly distinct from each other, SEF and BD, were keen on engaging further creating an interesting opportunity for comparison. The DeWalt group wanted to see preliminary results and potentially borrow processes co-created with SEF and BD. SEF (referred to hereafter as "B1") belongs to the Industrial division which serves business clients, while BD and DeWalt serve end-consumers (referred to hereafter as "B2" and "B3").

4.1.1 RQ1: Identifying valued SDMT ingredients through co-creation

Research methods employed to address RQ1 center around co-creating the sustainable design process for B1 who agreed to engage in the full study. I also interacted with B2 and B3 upon completion of the co-creation process with B1. B2 sought to adapt B1's process in a lightweight format to their context, while B3 borrowed B1's process as-is.

Co-creation Context and Participants

I worked with six participants (P1 - P6) from the B1 who were either engineers or managers. All participants were male, and aged 30-50 years. They all had 5+ years of experience in their roles, with the most senior participant having 15 years of experience at SBD. B1 was committed to this project as they were already planning to overhaul their PD process to incorporate sustainability considerations. The co-creation process steps in the next subsection detail the process that the participants engaged in.

Document Analysis

I then analyzed company documents on existing resources applied in the PD process to support both mandatory and voluntary sustainability tasks. This involved reviewing documents on various regulations and recommendations compiled by the CSR team.

Co-Creation Process

This subsection details the steps involved in the iterative process of co-creating a sustainable design process or framework to be systematically and repeatably incorporated into their PD practice. The steps are summarized in a flowchart in Figure 28.

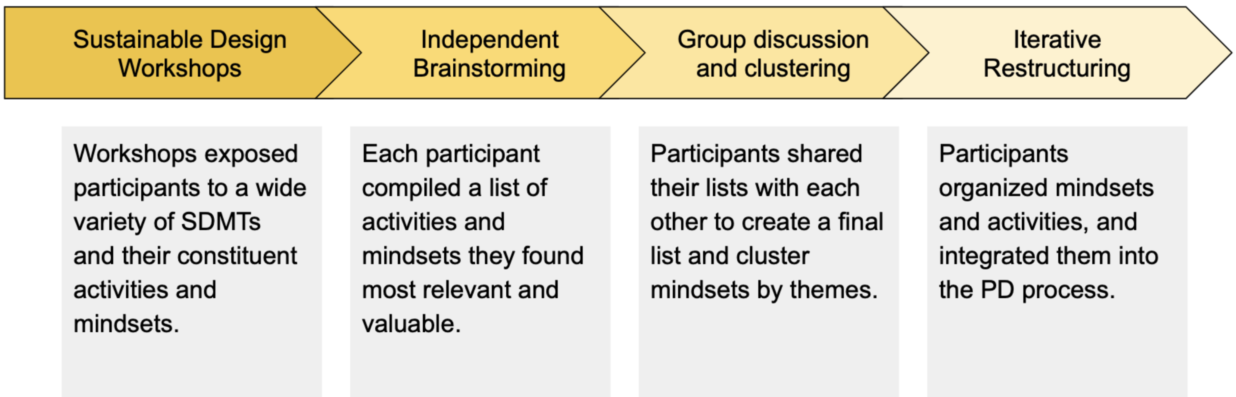

Figure 28: Stages of the co-creation process that the SEF participants engaged in.

Step-1 Conducting Sustainable Design Workshops: I started by conducting two workshops, lasting four hours each, with six participants from SEF to introduce them to a variety of SDMTs including:

1. Lunar Field Guide
2. Ellen McArthur Foundation's Circular Design Guide
3. Synapse Sustainable Design Guide
4. Okala Design Practitioner
5. Cradle-to-Cradle Certification
6. Life Cycle Assessment
7. Whole System Mapping
8. The Natural Step
9. Biomimicry

These methods were chosen for their diversity in approaches. Each of the above SDMTs constitute several activities (A) and/or mindsets (M). Literature shows that designers seldom apply the entire SDMT as a tunnel process [19]; instead they opportunistically pick and choose strategies from different SDMTs and apply them as necessary [20]. With this outlook, each of the nine SDMTs were broken down into constituent activities (A) and mindsets (M), listed in Table A3 of the appendix. According to [22], *"activities"* are tasks that are physically performed, while *"mindsets"* are aspects that are mentally considered. We collectively refer to activities and mindsets as *"strategies"* here.

Step-2 Independent Brainstorming and Research: Table A1 was shared with the participants who were asked to individually come up with their own list of strategies they thought were valuable to their practice. They were asked to ensure that the strategies they select are relevant and applicable across a wide range of projects that their business unit engages in. Participants were given a week to complete this step, which resulted in the generation of five different lists, one from each participant. The sixth participant was unable to submit a list for consideration.

Step-3 Group Discussion and Clustering: All six participants and I then convened to share what strategies they had selected and why. The strategies that appeared most often were included in the final list, while participants debated the rest. The final list included 42 mindsets grouped into 11 categories, and 7 activities added as tasks to the PD process.

Step-4 Iterative Restructuring: We then engaged in a multi-week-long iterative restructuring process to experiment with different ways to best integrate the strategies into their PD process. The details of changes made during each iteration highlight the constraints within the existing PD process as well as what approaches were perceived to be efficient. The iterations are represented in Figure 30 of Sec 4.2.1.

This concluded the co-creation process with the final outcome being a tailored sustainable design process that can be systematically and repeatably applied across projects at B1. As a reminder, these strategies consist of both mindsets and activities, which integrate differently. The outcomes were shared with the rest of B1's employees, as well as other business units. Representatives from B2 met with me later to discuss tailoring a lightweight version of these resources to their context, while B3 sought to borrow and apply these processes as is.

4.1.2 RQ2: Assessing both Up-front Receptivity and Long-Term Retention

Upfront Receptivity Interview

Upfront receptivity was assessed during the recruitment interview (Figure 27) conducted with participants across business units. Additionally, they interacted with me both one-on-one and in groups when I was embedded in the company. Qualitative insights gathered from the interviews, discussions, and ethnography shed light on the barriers and drivers to sustainable design integration at SBD. Key themes are listed in Sec 4.2.2.

Longitudinal Study to Assess Retention

The longitudinal phase of the study tested the RQ2 hypothesis that engaging in a co-creation process improves retention and use of the sustainable design process following its development. I initially worked from June - August, 2021 to co-design the sustainable design process with B1. I then left the company and returned after a year (Jun

- Aug, 2022) to evaluate retention and application of the process. The evaluation of retention took two forms:

1. Follow-up interviews with the employees from B1, B2, and B3, who engaged to varying degrees in the co-creation process
2. Document analysis and support on the project that the process was applied to.

Document analysis addresses RQ2 by highlighting the differences in the level of retention across B1, B2, and B3 who all had varying degrees of engagement. In addition, thematic analysis of interviews identifies factors unique to this company's context that either bolster or hinder receptivity and long-term retention.

Data Analysis

Data gathered during the co-creation process primarily consisted of:

- **Qualitative data** in the form of transcripts of recordings made during interviews along with documents analyzed.
- **Semi-qualitative data** in the form of documentation gathered from participants during the brainstorming sessions, group discussions, and iterative restructuring.

Thematic Analysis: Qualitative results in the form of transcripts of recordings were analyzed thematically to extract critical insights (Braun and Clark, 2006). I initially coded the interviews, which were then reviewed by another author to ensure intercoder reliability. All disagreements were discussed and resolved, and the key themes extracted are detailed in Sec 4.2.2.

4.1.3 RQ3: Evaluating the Impacts of Integrated Methods on Sustainable Outcomes

As a reminder, the third research question examines whether the co-created process, when applied in practice, indeed generates more sustainable outcomes. The project examined here was initiated when I was away, and was still in the early stages of PD when I returned for the longitudinal study. I proceeded to support a team from B1 on their application of the sustainable design process. Additional methodological details about these activities, step-by-step results from application of the sustainable design process, as well as the final takeaways from the quantitative assessments are detailed in Sec 4.2.3.

4.2 Results

The following sections describe our qualitative, semi-quantitative, and quantitative findings from the co-design process, evaluating upfront receptivity, retention based on engagement with the co-creation process, and a detailed case study conducted with B1.

Results are organized around the research questions relating to: 1) what aspects of existing SDMTs bring value to practitioners; 2) whether co-creation or other factors aid receptivity and adoption of sustainable design practices; and 3) whether applying the process resulted in a reduction in environmental impacts on a real client project.

4.2.1 RQ1: What Do Practitioners Value in Existing SDMTs?

The participants from B1 engaged in the steps detailed in Sec 4.1.1 to co-create a sustainable design process for their business unit. The following subsections detail the results and insights gained from each step of the co-creation process based on analyzing the documentation produced.

Reviewing Existing Practices and Conducting Workshops on Existing SDMTs

I started by reviewing existing sustainability practices created by the CSR team that were detailed in past PD documentation. Overall, SBD follows a milestone PD process illustrated in Figure 29, which at SEF takes up to two years to complete and includes 200+ existing activities performed by stakeholders from 20+ different divisions.

SEF Milestone Process								
MILESTONE	MS0/1	MS2	MS3	MS4	MS5	MS6	MS7	MS8
Title	Define and Initiate	Develop	Control	Prototype	Pilot	Industrialize	Launch	Post-Launch

Figure 29: SEF's PD process is divided into eight milestones

Document analysis revealed that the resources provided by the CSR team focused more on mandatory compliance aspects rather than voluntary sustainable design aspects. Some activities included in the PD process to address regulatory compliance include:

- Ensuring that every supplier is in compliance with SBD's Restricted Materials Specification including substances like asbestos, lead etc.
- Ensuring that products that require it have the California Proposition 65 warning.

The CSR team had also created "ECOSMART guidelines" to provide sustainable design support. However this only included examples of methods without tailoring to the context or guidance on which methods to apply when. Interviews with SEF employees showed that they were eager to come up with a "systematic", "structured", and "data-driven" process to voluntarily integrate sustainable design into their PD practice.

Conducting Workshops on new SDMTs

I initiated the co-creation process by conducting workshops on a wide range of SDMTs which can be broken down into individual sustainable design activities and mindsets, as listed in Table A3 of the appendix. This allowed the participants to mix and match strategies that they found most relevant. The research team ensured that the SDMTs taught in the workshops included quantitative and qualitative methods, and a variety of formats. The workshops helped build a baseline understanding of sustainable design literature and terminology.

Independent Brainstorming: What strategies did each participant value?

Following the workshops, participants were given a week to select a set of strategies that they valued the most from Table A1. They were instructed to ensure that these strategies would be widely applicable across projects in their business unit. This exercise led to five different sets of strategies; one participant did not submit a list. They are captured in Table A4 in the Appendix. Several insights can be drawn from these lists including:

- **Participants identified more mindsets than activities:** P4 said, *"the PD process already has a lot of tasks, and I don't want to add more"*.
- **Similarities across participants' lists:** All participants selected strategies from similar themes such as: energy use sustainable materials. We identified that this gravitation was influenced by what employees heard from leadership. P3 said, *"these are topics we often hear when we think about sustainability"*.
- **Unanimous agreement to use LCA:** Everyone agreed that it was important to be guided by the results from a quantitative analysis like LCA. P2 said, *"it is important to rely on facts and numbers"*. We observed that engineers especially tended to take sustainable design recommendations seriously when they were based on LCA results.

- **Skew towards functions they practiced:** A majority of the considerations identified focused on sustainable materials and manufacturing, as these areas were within scope of their work. I had to nudge participants to broaden their scope to look at the entire life cycle.

Group Discussion and Clustering

Following the independent brainstorming, participants shared their lists with the rest of the group and debated why a certain strategy was considered valuable. Through this process, they arrived at a final list of 42 mindsets that were clustered by themes as shown in Figure 30.

After further refinement, the final list of themes included: product life, product versatility, product complexity, sustainable materials, resources consumed during manufacturing, resources consumed during use, impacts from packaging, emissions from distribution, end-of-life management, and compliance with regulations. Seven activities were also shortlisted to be included in the PD process. These are shown as bullets in Fig 32. (e.g., "work with the Pugh matrix") and explained in the next section.

Iterative Restructuring

Upon compiling a list of activities and mindsets deemed valuable to include in the PD process, the participants and I explored a) various formats to organize the 42 mindsets identified, and b) decide where in the PD process the activities should be performed. This process took an iterative approach, detailed in the flowchart in Figure 31.

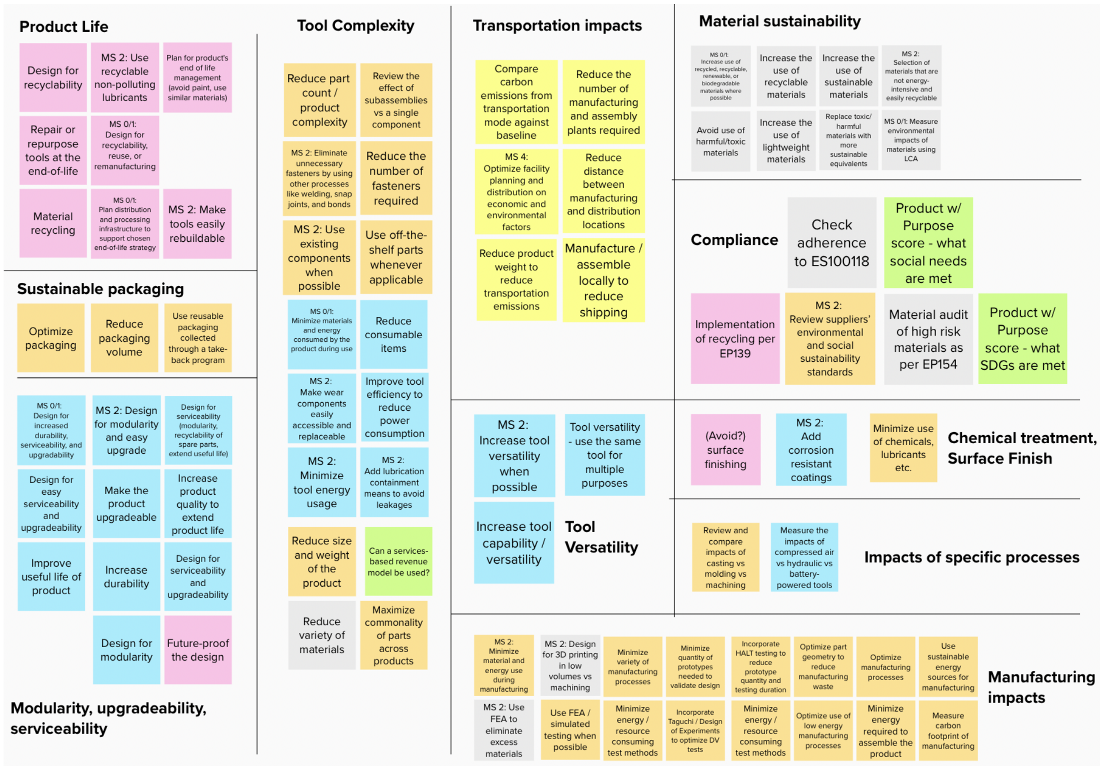

Fig 30: Collaboratively clustering mindsets into themes

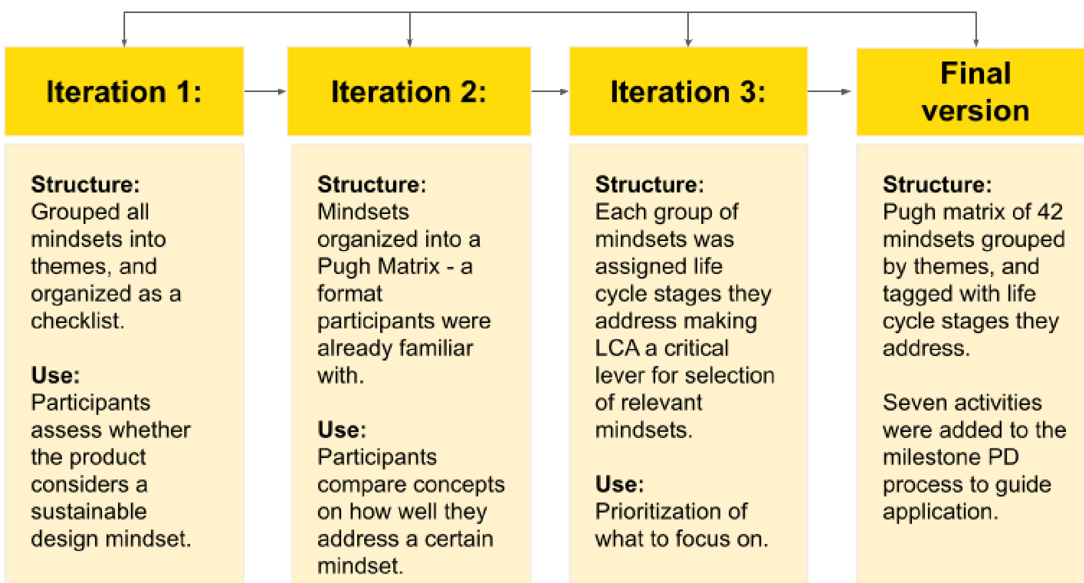

Fig 31: Flowchart describing various iterations to arrive at the final structure for integrating all the activities and mindsets chosen by participants.

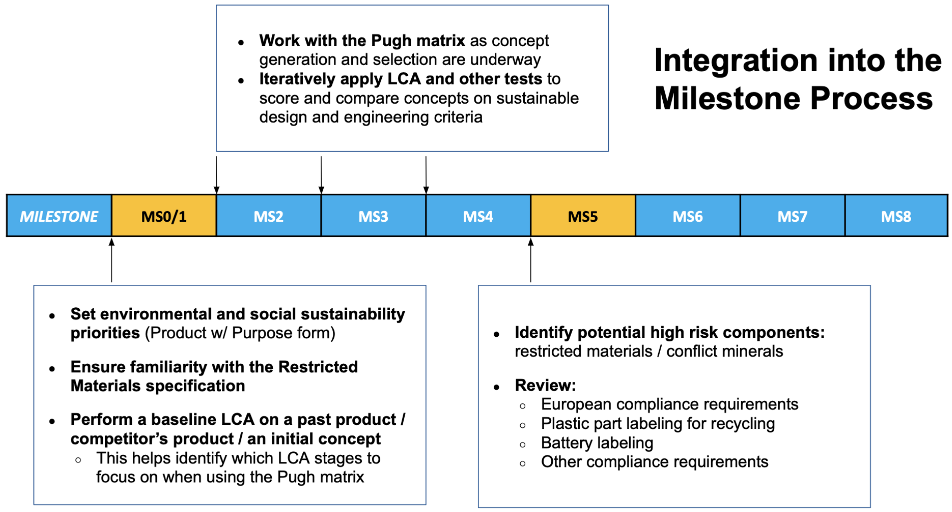

Figure 32: Activities added to the milestone PD process

The first iteration involved grouping all the mindsets into a checklist that designers can review during PD. Additionally, participants agreed that it would be valuable to consider these mindsets repeatedly through the early PD stages.

The second iteration explored other formats besides a checklist. P3 said, *"it's easy to check a box on a checklist without fully considering it"*. P1 suggested integrating it into formats they already used such as: a Pugh matrix, the TRIZ method, etc.

The third iteration grouped the mindsets by the life cycle stage it most impacted, which would be deduced through LCA. Participants agreed that having levers to shortlist what to focus on would improve efficiency and ensure data-driven choices.

In the final iteration, participants settled on a Pugh Matrix as the structure for organizing the mindsets. They were highly receptive to this structure because it was used routinely for engineering decisions, highlighting the importance of leveraging familiar tools as a vehicle for the uptake of new methods. The final pugh matrix of mindsets is depicted in Table A5 of the Appendix, which was filled in as part of the case study discussed in Sec 4.2.3. The activities to be added to the PD process, as shown in Figure 32, were also finalized.

A Pugh matrix is a decision-making tool that allows users to compare product concepts against a datum on various criteria. These concepts are scored as better than, similar to, or worse than the datum. The total score reveals which concept is the biggest improvement over the datum. This matrix of mindsets both informs design and compares concepts.

Upon conducting a preliminary LCA on the datum participants identify which life cycle stage has the biggest impacts which informs which mindsets are most relevant. Participants consider them as they design concepts, and eventually use the Pugh matrix to rate them to pick the best alternative. The Pugh matrix of mindsets along with Figure 32 depicting activities added to the PD process form the overall sustainable design process that the SEF team co-created. This process is expected to be revised over time.

Adoption in other business units

In the following weeks, these resources were shared with B2 and B3. As a reminder, B2 and B3 are distinct from B1 in that they both function as business-to-customer, while B1 sells to other businesses. They also differed in their level of engagement with the co-creation process.

B2 business unit:

Two participants from B2 who had been spearheading their sustainability initiative met with me to review the B1 resources and decide how to tailor it to their teams. P1 shared that, *"the PD cycle is a lot faster at B2 than at B3; it will be difficult to fit something so elaborate into the process"*. P2 added that, *"B1's b2b (business-to-business) model is different from B2's b2c (business-to-customer) model"*. I learned that it was important for

B2 to have the strategies translate to a known ecolabel so the sustainability benefits could be communicated to their end-customers. Together we identified four areas that were important, including: energy use, materials, packaging, end-of-life. P1 and P2 would go on to compile relevant ecolabels and try to meet them with engineering teams. They agreed to check-in the following year to share progress.

B3 business unit: B3 invited me to share the sustainable design process developed with B1 with their engineers through a lunch & learn session organized by the group. They hoped that interested teams would seek out these resources and adopt them as necessary into their projects. For B3 products, sustainability improvements are more expensive both to the company and the customers, resulting in greater inertia to change.

The next section discusses the upfront receptivity as well as barriers and drivers to sustainable design adoption. It also examines the effect of co-creation on long-term integration, comparing retention at B1, B2, and B3.

4.2.2 RQ2: Does the process of co-creating a custom sustainable design process enhance receptivity and long-term integration into practice?

I hypothesized that the co-creation of new sustainable design processes with the employees would improve adoption, ownership, and further dissemination of these practices. The longitudinal study to evaluate retention across B1, B2, and B3 who each had varying levels of engagement with the co-creation process, addresses this.

This section first details the various barriers and drivers to the adoption of the sustainable design process as derived from a thematic analysis of the recruitment interview detailed in Figure 27 and other interactions and meetings that I was part of at SBD. Key themes, agreed upon by all the authors, are: 1) investor interest in ESG, 2) grassroots initiatives led by concerned employees, 3) market competition and brand reputation, and 4) regulatory pressures. These aspects set the context for existing receptivity and willingness to adopt new practices. Afterwards, I discuss whether co-creation enhanced retention.

Investor interest in ESG

Prior research, discussed in Sec 1.4, shows that there is increased investor interest in reporting on environmental, social, and governance (ESG) impact metrics. As such, the CSR team has set: a) company-wide sustainability targets, as well as b) report status and progress using standards such as the Carbon Disclosure Project and the global reporting initiative. I first joined the company as an intern in 2021, shortly after the publication of SBD's first ESG report. Fig A1 included in the appendix is taken from this report, and shows a timeline of SBD's ESG evolution. It shows how most of these major top-down changes occurred in recent years.

These pressures trickled down in not so subtle forms. For example, we heard reports of how senior corporate leadership and business unit leadership often *"grilled teams on their project's contributions to ESG"*. This led to a steady increase in sustainability related inquiries made to the CSR team. Pressures from fielding these requests and reporting on multiple standards led to an expansion of the team.

An increased budget led to investing in the development of a simple spreadsheet-based LCA calculator, created by a third-party sustainability consultancy. This tool only focuses on material and manufacturing impacts. Figure 33 is a screenshot of the calculator.

Top-down pressure drives grassroots initiatives

Recent top-down initiatives and investments fueled grassroots efforts from concerned employees leading to greater awareness of sustainability. To nudge this along further, a CSR team member said they were further increasing *"awareness of the ESG goals* *through lunch-and-learn sessions and social media"*. Each week they host talks on an ESG-related topic such as, *"promoting sustainable procurement practices"*, *"interpreting emissions numbers"*, *"differences between scope 1, scope 2, and scope 3 emissions"*. I also gave a talk on *"measuring impacts using LCA"*. These talks *"improved curiosity and receptivity"*, leading to a greater enthusiasm, claimed one participant.

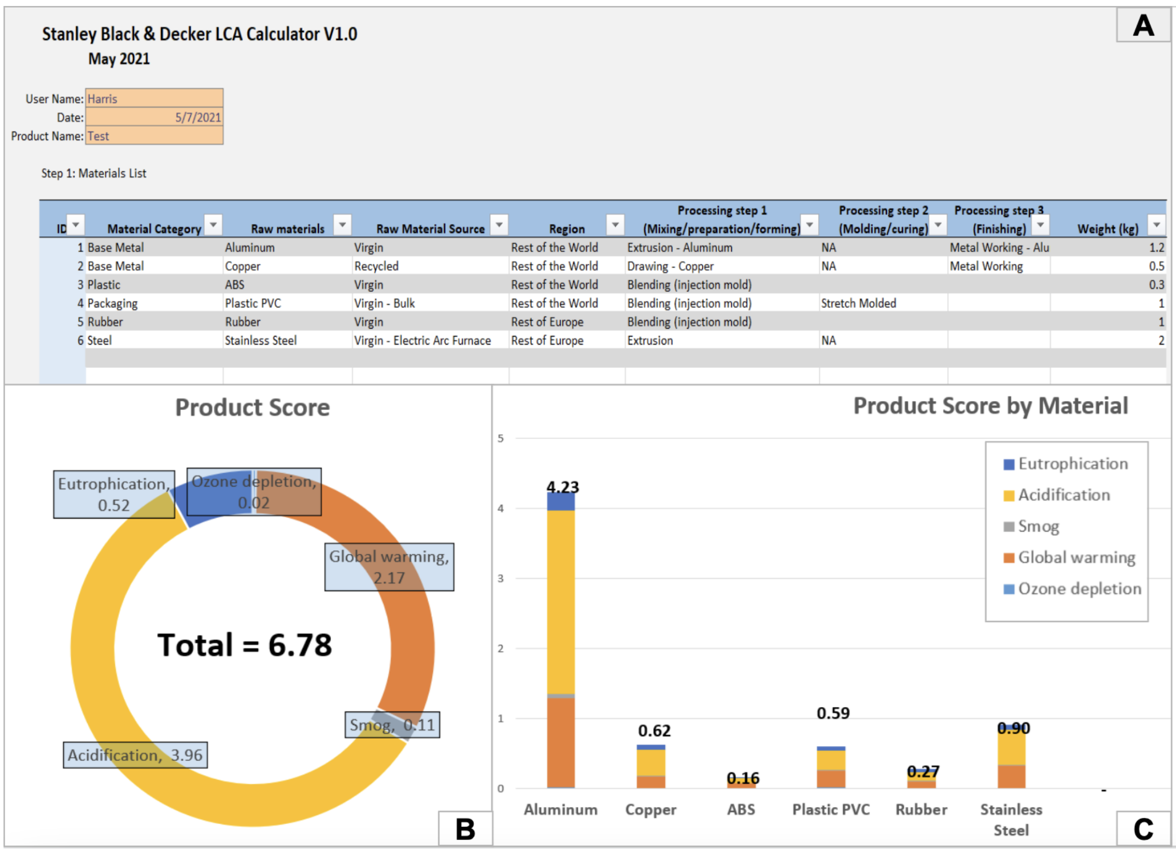

Figure 33: Screenshot of the spreadsheet-based LCA calculator commissioned by SBD

A group of employees, referred to as the *"ESG champions"*, from different business units met regularly to share best practices. This group formed an interface between the CSR team and their colleagues, nudging them to consider sustainability. A small group of ESG champions worked on a months-long project to identify, test, and compile a database of sustainable material alternatives. With support from the CSR team, this team identified companies developing advanced materials. They meticulously tested these materials in-house to validate properties as well as assess feasibility and manufacturability.

The sustainable materials database has since become a trusted resource for engineers looking for alternatives. One engineer who recently used it to find a new supplier said, *"I trust it because it is compiled by other engineers like me as opposed to a corporate team"*. This is an example of how collaboration between grassroots initiatives and top-down corporate sustainability teams is mutually beneficial. The grassroots initiatives provide credibility, while top-down support brings funding and workforce.

Market competition and brand reputation

So far we have looked at internal factors. Now we consider external ones such as market competition and brand reputation. A majority of B1's clients are automotive manufacturers seeking fastening equipment for their supply chains. The automotive sector has historically been subject to regulations such as tailpipe NOx and CO_2 emissions limits getting stricter in most geographies [88]. However, with the rise in electric vehicles the emissions burden is shifting from the automotive's use phase to its manufacturing phase. The manufacturing phase impacts entail energy and materials used during manufacturing as well as the embodied emissions of equipment used. These pressures played a big role in B1's receptivity to co-creating a sustainable design process.

B2 on the other hand makes power tools, and home appliances for end-customers seeking to use them at home. These tools are often sold in hardware stores like Home Depot in the US. B2 sought to *"revitalize their brand by appealing to younger consumers willing to pay for more sustainable products"*, according to one project manager from B2.

Overall, B2's focus was on communicating their sustainability gains to end consumers by distilling down B1's sustainable design process into marketable ecolabels and standards.

The B3 business unit however wanted to wait to see results from sustainable design integration at other business units within the company as well as competitors. The professional tools they produce are designed for professional construction workers. This makes the shift to sustainable products more expensive for the company, and their customers may not be willing to pay the premium for these products. This led to their limited engagement with the co-creation process.

Regulatory pressures

Regulations are another important external driver of the shift towards sustainability. SBD is a multinational company serving customers in North America, Europe, and Asia, with different regulations in different geographies. A compliance team is typically called on during the PD process to ensure that the product is in compliance.

However, there has recently been a growing concern around the advent of extended producer responsibility (EPR) regulations in Canada and the US. EPR is defined as *"a policy to promote environmental improvement of product systems by extending the responsibilities of the manufacturer to the take-back, recycling and final disposal of the product"* (Lindquist, 2000). In both Canada and the US, EPR policies have led companies to consider redesigning products and instituting take back programs [89].

During my work with SBD, the CSR team was grappling with the changing EPR landscape in Canada. EPR regulations were a motivating factor in the consideration of circularity in the battery-powered fastening device case study discussed in Section 4.2.3.

Does co-creation improve long-term retention?

As a reminder, I collected data across two summers, examining the company's evolving ESG efforts over time. Amendments to the PD process with sustainable design activities and creating the Pugh matrix of mindsets, co-created with the B1 group, simplifying these resources for B2's use, and B3's adoption of the practices as is, were all finalized during the first internship. The hypothesis is, *"is the level of engagement with co-creating a sustainable design process directly correlated to long-term integration?"*

When I returned to the company next Summer, she found that B1 had begun applying the process in practice on a new project. I also found that the resources had been officially added to the PD process. Section 4.2.3 details a case study of the application of the process in practice, and whether it led to sustainable outcomes.

B2 had also amended their PD process to add a few ecolabels to target; however, the application was limited. They had recently launched a sustainable product line called reviva™ using chemically recycled materials. But, it was unclear if this used resources from this study. B3, who had not engaged in co-creation, had not implemented the processes and resources they had borrowed from B1.

These results confirm that engaging in the co-creation of new sustainable design processes improves ownership, dissemination, retention, and successful application.

4.2.3 RQ3: How does a co-created sustainable design process lead to the development of more sustainable products and services?

This section both summarizes the application of the co-created design process to a new product development and also shows quantitative estimates of the product's environmental improvement, which were performed as part of the new design process. I went back to SBD the following year to evaluate retention and application of the co-created processes. I found that the B1 business unit had applied the process on a new project while I was away, and development was still underway. I then started supporting the engineering team working on the project.

Product context and research questions

B1 operates in a business-to-business context working with industries looking for equipment for in-plant and outdoor construction activities. This case study focused on developing a new line of fastening tools for the installation of commercial solar power plants in the United States for a client seeking to install solar plants with 6GW of total power generation capacity. Their new product concept involved electrifying the fastening tools to be powered by portable, rechargeable batteries. SBD's CSR team had been advocating for electrification, and finally gained buy-in to electrify tools that had previously been gas-powered. The sustainability benefits from this transition had not been fully verified. They were also considering piloting a takeback program to refurbish and extend the life of the tools. We identified the following questions that I could support them in answering:

1. Does the battery-powered fastening system produce less emissions than the gas-powered fastening system used previously for solar panel installation?
2. Is it economically feasible and environmentally beneficial to implement a circular supply chain to take back high-impact parts (batteries, electronic components) for remanufacture?

Applying the sustainable design process in practice

The team followed the sustainable design process laid out in Fig 6, starting by filling out the Product w/ Purpose checklist, familiarizing themselves with the list of restricted materials, followed by mapping out the systems being compared, and conducting a preliminary LCA. They used the Pugh Matrix to consider sustainable design mindsets as well as compare concepts throughout the PD process. Upon completing concept development, a more formal LCA was conducted. All of these steps are laid out in the following subsections, along with the takeaways from the results.

System Mapping

Following a quick review of the Restricted Materials Specification document at Milestone 0/1, they employed a system map scope out the boundaries of the system. This helped broaden their scope beyond the fastening tool to consider the other components required to successfully install a solar site. System mapping is a brainstorming and analysis activity derived from Whole System Mapping, taught during the workshops. Figure 34 shows the final system map comparing the two scenarios.

The system map includes the tool and all the other components required to successfully install a 50 MW solar site, forming the whole system. The gas-powered system includes five fastening tools, five hydraulic pumps, three all-terrain vehicles for transportation, and the bolts. The battery-powered fastening system to install 50 MW solar power capacity includes five fastening tools, five battery chargers, ten batteries, and the bolts.

The assumptions and calculations underlying the system map are detailed in Figure A2 in the Appendix. It is evident that the battery-powered fastening system is simpler than the gas-powered fastening system. The team then proceeded to perform a preliminary LCA.

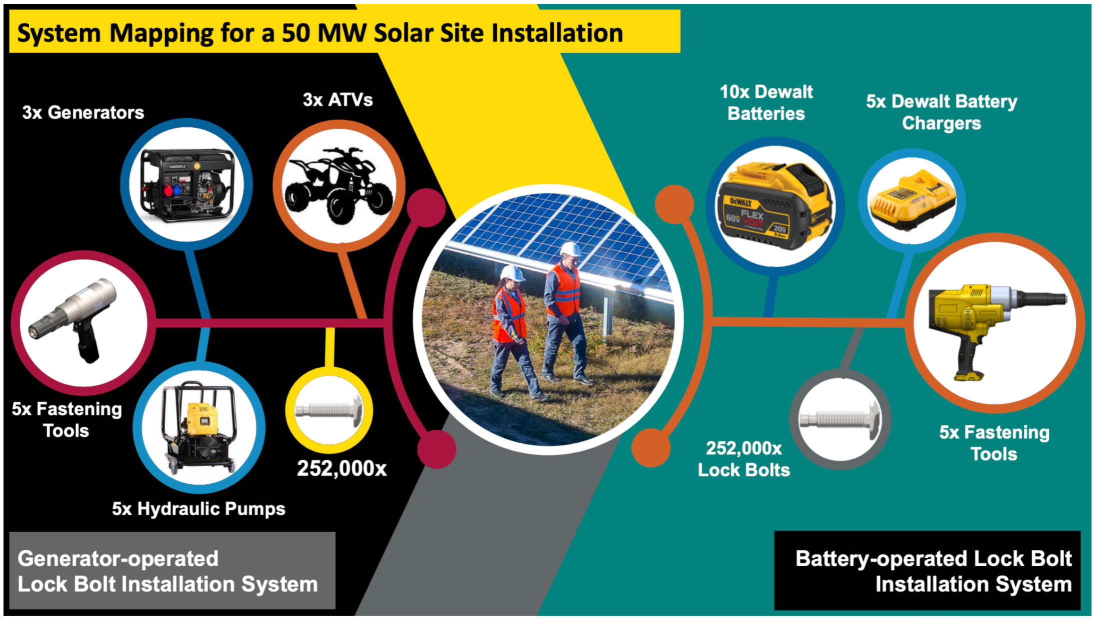

Figure 34: System map comparing the gas-powered fastening system to the battery-powered fastening system

Preliminary impact assessment

Preliminary analysis was a fast-track LCA using limited data with the spreadsheet-based tool (Figure 33) for the materials & manufacturing phase, while the use phase impacts were calculated manually. All calculations are included in Figure A2 in the Appendix.

Preliminary results showed that the battery and additional electronic components caused a slight increase in materials impact but use-phase benefits from avoiding gas far outweighed this as shown in Figure 35. The results confirmed the CSR team's recommendation to pursue electrification. It also led to discussions around circularity to extend the life of the high-impact parts such as the battery and electronic components. Together these results helped guide what mindsets to consider from the Pugh Matrix, detailed in the next subsection.

Applying the Pugh Matrix

The Pugh matrix served a dual-purpose of a) highlighting sustainable design mindsets they might not yet have considered, b) comparing the two systems on their merits and demerits. The filled out pugh matrix comparing the battery-powered tool to the gas-powered hydraulic tool is shown in Table A5 of the Appendix. The pugh matrix showed that the new electrified concept was either similar (using off-the-shelf parts) or worse (product weight and complexity) than the battery-powered datum, which is in line with the preliminary analysis. These insights informed the detailed design phase when the team conducted a more detailed LCA.

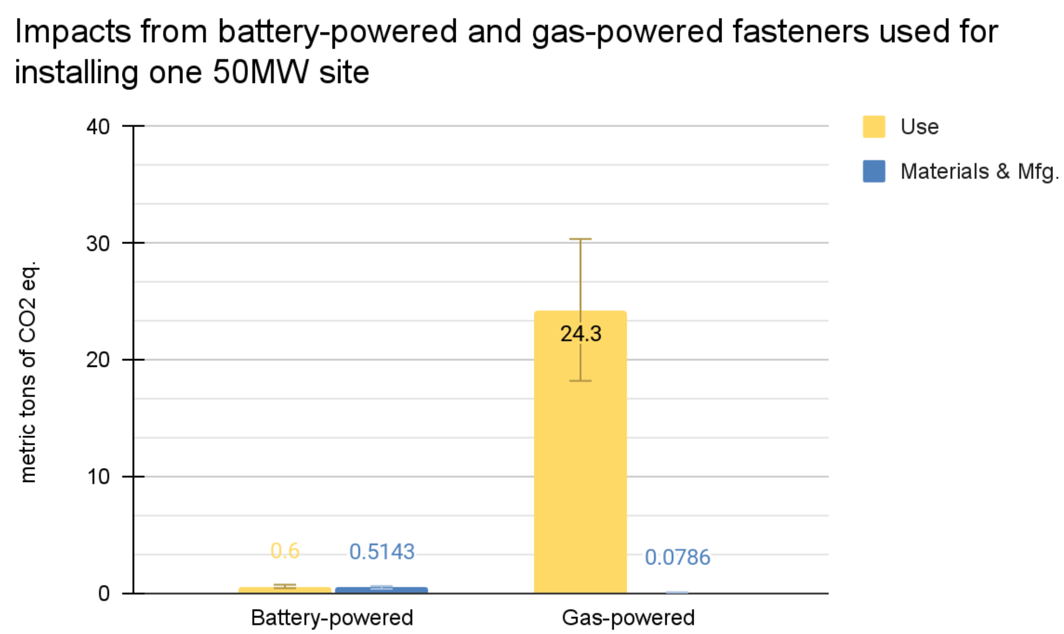

Fig 35: Results from preliminary LCA to assess how environmental impacts from the use phase of the product (yellow) compare to its materials & manufacturing (blue), for both the battery-powered and gas-powered versions.

Performing a detailed life cycle analysis

Moving further along the PD process to **Milestone 3**, the team compiled a full list of parts and sub-assemblies in the new battery-powered tool, enabling me to conduct a more thorough LCA. The system boundary for the analysis constituted the materials and manufacturing impacts of the battery-powered tool, and the energy consumed during use. The LCA was performed using the Sustainable Minds tool. An anonymized table of the BOM used is included in Table A6 of the appendix. These results, displayed in Figure 36, corroborated the insights from the preliminary assessment. There is a slight increase in materials impacts due to the use of a battery and new electronic components. However, the use phase impacts from the gas-powered system far outweigh them. The total impacts of the electrified design were estimated to reduce CO2 emissions by greater than 90%.

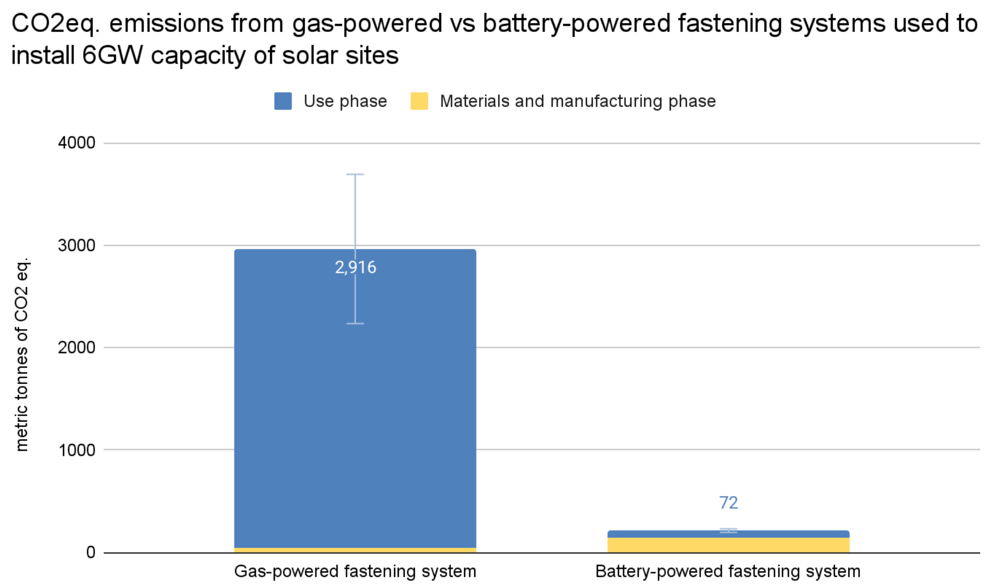

Fig 36: Comparing CO2 emissions of gas-powered and battery-powered systems by life cycle stage. Error bars show total uncertainty for both phases.

Design discussions following this assessment looked at ways to keep these high-impact components in use for as long as possible. Reusing batteries and electronics lead to both environmental and economic benefits by avoiding costs associated with EPR regulations. This led to the subsequent case-study asking the question: *"Is it economically feasible and environmentally beneficial to implement a circular supply chain to take back high-impact parts (batteries, electronic components) for remanufacture and reuse?"*.

The circular system takes back tools from the client to replace worn out mechanical parts while keeping the battery and electronics that can be used for longer. It was determined through testing that the parts highlighted in green in Table A6 in the appendix would need to be remanufactured.

The system boundary for the analysis constituted the materials and manufacturing impacts of the battery-powered tool, the energy consumed during the use phase, as well as the additional transportation emissions from reverse logistics for the circular supply chain. Impacts from the reused parts such as the battery were deducted based on the number of predicted reuses. Results from an LCA comparing the circular supply chain for the battery-powered system to the linear supply chain are shown in Figure 37.

The graph shows a ~30% reduction in impacts when implementing a takeback program to reuse the electronics and the battery in the tool. These promising results led the team to test the economic feasibility of such a system.

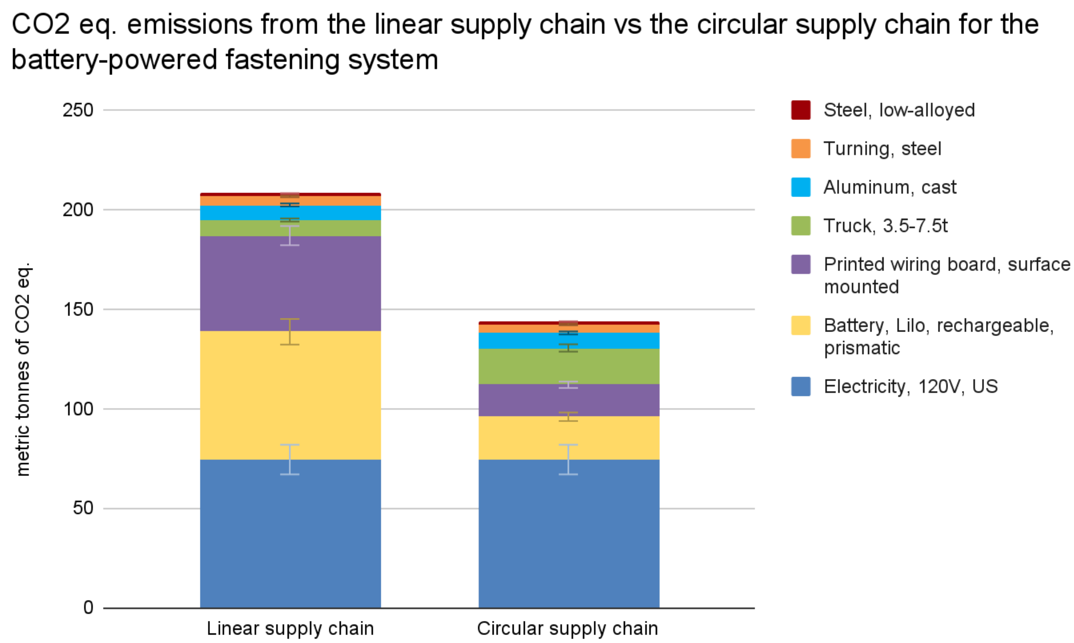

Figure 37: Comparing CO2 emissions from linear and circular supply chains. Error bars show total uncertainty for all items.

A preliminary margin analysis measured how the profit margin percentage is affected by the circular supply chain. In Figure 38, the virgin margin percentage represents the linear supply chain while the refurbished margin percentage represents the circular supply chain. Three different volume cases are considered (100, 250, and 500 units), where higher volumes lead to a lower selling price. Since these sales are all made to a single client, the volume of tools sold range from 100 (low), 250 (medium), and 500 (high). The graph in Figure 38 shows the difference in profit margins for each case. Table in the appendix lays out the calculations which accounted for a discounted sale price for the refurbished products, additional cost of transportation, and workforce.

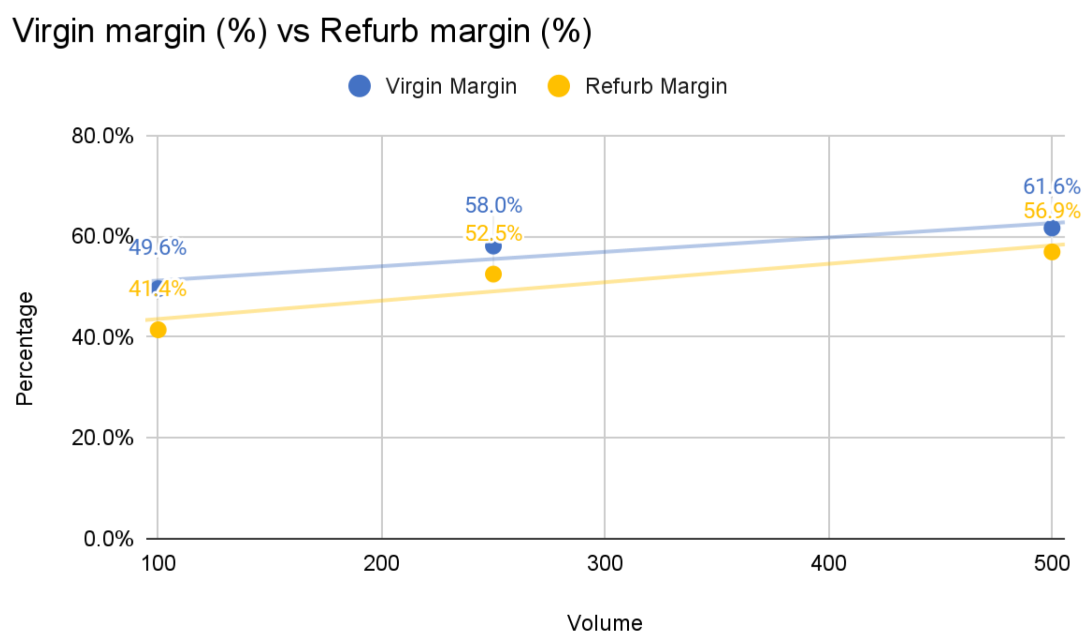

Figure 38: Graph comparing the profit margins between the linear and circular supply chains for three different production volume conditions (100, 250, and 500 units)

Results show that the circular supply chain does not majorly reduce the profit margin, and is expected to improve once the EPR costs of the linear supply chain are added. Additionally, future implementation of carbon taxes could further improve the circular supply chain's margin in comparison to the linear supply chain. Finally, further redesign to enhance refurbishment could lower refurbishment costs, thus increasing those margins.

4.3 Discussion

This study showed what SDMTs participants valued, and how they organized these strategies into a systematic sustainable design process to apply during PD. We also identified drivers and barriers to the sustainability transition. The longitudinal study showed how engagement with co-creation is correlated to long-term retention. Finally, the solar installation case study showed how applying this process leads to tangible sustainability benefits. The results from this case study are a testament to how design and business model changes implemented early-on in PD, and validated by data-driven life cycle analyses, leading to big reductions in impacts.

The following subsections summarize the ongoing impact of this study at SBD, and generalizable takeaways for researchers and practitioners seeking to incorporate sustainable design into their PD practices.

4.3.1 Ongoing impact of this study within the company

The longitudinal study with B1, from co-creation to implementation, provided a blueprint for other business units seeking to adapt their PD process to consider sustainability. Upon wrapping up co-creation with B1, the resources were shared with other business units including B2 and B3 through talks hosted by the CSR team. This vastly improved awareness of sustainability across the board. The company had so far only anecdotally pursued electrification as a sustainability strategy. The solar installation case study provided evidence that electrifying previously gas-powered systems reduces environmental impacts enormously. Further, modularizing the tool to enable refurbishment was the most progressive business model consideration yet. It made all stakeholders aware of the value of circularity to avoid future costs associated with EPR. The CSR team is continuing to explore similar case studies and projects across various business units, as well as helping teams incorporate a sustainable design process.

4.3.2 Comparison against a prior study conducted at an engineering consulting firm

We conducted a similar study at an engineering consultancy firm, Synapse, which was in a very different context (Chatty et al., 2022). In this subsection, we discuss the similarities and differences between the two contexts.

Synapse had about 200 employees when the study was conducted, a majority of whom were mechanical, electronics, or firmware engineers in addition to project managers. They worked with clients across a variety of industries on hardware consumer electronics. I was embedded at Synapse as an intern, similar to SBD, to co-create their sustainable design process. A longitudinal study showed that its application on a diverse set of projects led to more sustainable outcomes.

One key difference that impacted the co-creation process was that Synapse did not have any pre-existing sustainability resources in place, giving me a blank slate to work with. At SBD, I had to incorporate existing resources generated by the CSR team as well as account for the ESG goals set by company leadership. Another important difference was that the Synapse PD process was much less rigid. Any new changes required buy-in from fewer stakeholders, improving the pace of adoption overall. These differences combined affected what SDMTs participants valued. Since the Synapse PD process had more flexibility, participants included more new activities than at SBD.

However, despite major differences in context, there were several similarities. Both companies recognized the value of conducting LCAs early-on and iteratively throughout the PD process to guide the selection of sustainable design strategies as well as track progress towards goals. In both cases, engagement with the co-creation of sustainable design processes was directly correlated with retention of these practices. This was particularly clear at SBD, where each business unit: B1, B2, and B3, had varying levels of engagement. Other generalizable takeaways are discussed below.

4.3.3 Generalizable takeaways from this study for sustainable design research

The interviews and ethnographic work informing receptivity and retention offer valuable nuggets for researchers and industry practitioners working on organizational change towards sustainability. These takeaways are listed below:

1. Big top-down investments in the form of new hires, purchasing licenses to assessment tools, and pursuing projects targeting sustainability provide much-needed motivation.
2. Publicly setting science-based sustainability targets and reporting on standards like CDP, meet investors' expectations and improve brand reputation.
3. Top-down support bolsters grassroots initiatives by providing both funding and recognition, such as in the case of the sustainable materials database (Sec 4.2.2).
4. Collaborations between grassroots initiatives and corporate-level teams are mutually beneficial, with the former providing credibility and implementation, and the latter providing resources.
5. Employees' sustainability priorities are influenced by what aspects are touted by leadership. SBD employees considered electrification and packaging materials to be critical as these topics were most frequently discussed in the company.
6. Engineering-heavy companies like SBD value recommendations made based on quantitative results from LCA.
7. Leveraging familiar structures and methods, such as the Pugh Matrix, improves uptake and retention of new processes.
8. Client or end-consumers' demand for sustainable products and services is yet another critical driving factor. Sustainability provides key differentiation.

9. In the business-to-business context of B1, their clients are setting ambitious targets to decarbonize. This pressure trickles down to their suppliers, like B1.
10. Tracking industry sustainability targets when selling to businesses can help pitch sustainable offerings as a way to improve the clients' reputation and reporting.
11. In the business-to-consumer context of B2, marketing sustainable products using ecolabels appeals to sustainably-minded consumers willing to pay a premium.
12. Finally, regulations such as EPR provide financial incentives to adopt circular supply chains to keep batteries and other high impact parts out of landfills.

The case study in Sec 4.2.3 demonstrated to the company how strategies like electrification promoted by leadership does in reality reduce emissions. Demonstrating improvements in environmental impacts on a client project improved credibility and receptivity among more skeptical teams.

In conclusion, this case study shows a correlation between the level of engagement in co-creation and long-term retention. The application of the process in practice the following year on a client's project confirms this. Additionally, the process led to tangible improvements in environmental impacts. When coupled with the case study conducted at Synapse, we see that despite major contextual differences, there are several generalizable takeaways for sustainability researchers and professionals leading such work in industry.

Chapter 5. Discussion

My research focuses on the two key challenges presented by the "ecodesign paradox", illustrated in Figure 1, and defined as the divergence between product knowledge and possible environmental improvements over the PD timeline [10], [90]:

1. Practitioners face barriers in quantifying the environmental impacts of their design decisions early-on in the PD process.
2. Practitioners face barriers in translating the environmental impact results generated by LCA tools into actionable design decisions.

In this section, I start by reviewing how my thesis addresses these challenges by summarizing how the research questions from each individual chapter are answered. Chapter 2 focuses on Challenge #1, while Chapters 3 and 4 focus on Challenge #2.

5.1 Summary of Research Questions and Answers

Table 7 summarizes the list of research questions encountered throughout the thesis chapters that address the two challenges described above.

Table 7: Summary of research questions across thesis chapters addressing the two main challenges identified

Challenges	Chapter	Research Questions
Quantifying environmental impacts of design decisions early-on in product development (PD)	2	How might we design life cycle assessment (LCA) software that is easy to learn and use, and is accessible to novice users during early-stage PD?
	2	How might such interactive software improve the overall workflow of performing LCA in these situations and make sustainable product development decision-making more efficient?
	2	How might such efforts help bridge the human-centered computing community and sustainability practitioners to collaborate on better

		digital sustainability tools for the future?
Barriers in translating LCA results into actionable design decisions leading to sustainable outcomes	3	What factors drive the company's receptivity to incorporating various SDMTs into their PD practice?
	3	What do practitioners value in existing SDMTs?
	3	How does the process of co-creating a customized sustainable design framework enable its integration into the company's PD practice?
	3	How does the framework support continued consideration of sustainability in the company's PD practice over time — or if it fails to do so, why?
	4	What do practitioners value in existing SDMTs?
	4	Does the process of co-creating a sustainable design process enhance receptivity and long-term integration into practice?
	4	How does a co-created sustainable design process lead to the development of more sustainable products and services?

5.1.1 Addressing research questions focused on Challenge #1

Challenge 1 centers around how we might help practitioners quantify the environmental impacts of their design decisions during the early stages of PD. This was mainly addressed as part of Chapter 2 which is organized around two research projects: 1) User and market research of existing LCA tools and 2) Design and development of a novel LCA tool tailored to PD practitioners' needs.

User and market research of existing LCA tools

This project focused on evaluating the ability of existing LCA tools to meet the needs of PD practitioners, and was conducted on-site at Synapse. Participants learned to use a variety of existing LCA tools ranging from industry-standard tools such as GaBi and SimaPro to simplified tools such as Ecolizer and Sustainable Minds.

Qualitative methods such as interviews, group discussions, and think-aloud tests were used to gather feedback on both usability aspects like learnability, ease-of-use (effectiveness and satisfaction), as well as LCA specific aspects like breadth and depth of databases available. The think-aloud test involved users sharing their interactions with the tool while speaking through them which allowed me to identify pain points.

Finally, a survey was conducted with participants to rate the tools on a list of factors: learnability, ease of use, breadth & depth of databases, effectiveness of visualizations, reliability of results, and cost.

Results from this study showed that none of the tools fully addressed all of the challenges posed by the eco-design paradox to the application of LCA in early-stage PD practice, opening up an opportunity for the design and development of a novel tool to fill this gap. Insights extracted from a thematic analysis of the qualitative data resulted in the following design questions for the development of the new LCA tool:

1. How might we manage the time constraints affecting the application of LCA in a fast-paced PD context?
2. How might we make LCA results more reliable by accounting for underlying uncertainties?
3. How might we facilitate iterative refinement of models?
4. How might we support interpretation and communication of LCA results?

Design recommendations proposed in this study were incorporated into the subsequent design and development of EcoSketch.

Design and development of a novel LCA tool tailored to PD practitioners' needs

Having identified the gap in existing LCA tools' ability to meet the needs of PD practitioners, I decided to design and develop a tool tailored to this target audience. This work is built upon prior work at UC Berkeley on the FocusLCA tool, and was performed in collaboration with the DALI Lab and EarthShift Global.

Qualitative feedback was gathered from practitioners in the form of interviews and think-aloud tests, where participants would share their thoughts, questions, and pain points. Evaluation of the final prototypes revealed that participants valued the following aspects about EcoSketch:

1. Flexibility,
2. Learnability,
3. Ability to account for Uncertainty,
4. Easy Sensemaking of Results, and
5. Error Handling.

Semi-quantitative feedback gathered through a system usability scale (SUS) survey showed that practitioners appreciated Ecosketch's learnability, overall consistency, and cohesiveness. Practitioners felt that the tool was not too complex, and that they would not require assistance from an expert to use it, which was a key objective. .

Quantitative tests evaluated the efficiency of EcoSketch's workflow in comparison to Ecolizer (the control tool) when performing an LCA in the early stages of PD. Figure 15 showed a striking improvement in the time taken to complete the task when using EcoSketch, proving the tool's value in a fast-paced PD environment.

The work also touches on how productive collaborations between the sustainability and the human-computer interaction communities can lead to the development of other valuable digital sustainability tools for industry, enabling them to achieve ambitious and critical climate targets.

Together the research detailed in Chapter 2 showed how existing LCA tools do not meet the needs of industry PD practitioners, opening up an opportunity for me to make a tool that fills this gap, thereby addressing Challenge #1.

Table 8: Solutions to research questions addressing Challenge #1

Research Questions	**Solutions**
How might we design life cycle assessment (LCA) software that is easy to learn and use, and is accessible to novice users during early-stage PD?	Through iterative prototyping of designs, informed by usability heuristics, and based on regular feedback from users.
How might such interactive software improve the overall workflow of performing LCA in these situations and make sustainable product development decision-making more efficient?	The EcoSketch workflow allows users to under-specify low impact parts thereby focusing their time and attention on hotspots.
How might such efforts help bridge the human-centered computing community and sustainability practitioners to collaborate on better digital sustainability tools for the future?	Exposes the SHCI community to opportunities in sustainability tools for industry, and makes sustainable design researchers aware of the value of adopting HCI principles.

In the next section, I summarize how the research detailed in Chapters 3 and 4 addresses Challenge #2, along with solutions to each research question.

5.1.2 Addressing research questions focused on Challenge #2

Challenge 2 centers around how we might help practitioners translate the environmental impact results generated by LCA tools into actionable design decisions leading to sustainable outcomes . This was mainly addressed as part of Chapters 3 and 4 which is organized around two research projects conducted at partner companies Synapse and SBD respectively. The work done in both chapters was guided by similar research questions, listed in Table 8.

Case study conducted at Synapse

The case study at Synapse was conducted when I was embedded at the company as an intern. This allowed me to observe, interview, and co-create a sustainable design framework tailored to their PD process. This project showed that engaging practitioners in an iterative co-creation process improves receptivity and long-term retention, as shown by the projects it was applied on (Fig 25) in the years after the study.

Qualitative data was collected in the form of interview and focus group discussion transcripts that were thematically analyzed to extract insights. An iterative, participatory, co-creation process, depicted in Figure 18, was employed to ensure that the final framework was tailored to the company's needs. Participants were exposed to a wide variety of strategies extracted from existing SDMTs, listed in Table 6, to help identify those that were most relevant to their context.

Through five separate iteration cycles depicted in Figure 20, the final framework was constructed whose application workflow follows Figure 24.

The framework guides practitioners through measuring the environmental impacts of their product concepts using simplified LCA tools, identifying critical hotspots, and selecting appropriate strategies from an initial list of 22 different strategies. The selection process is made simpler because the strategies are tagged by the life cycle stages they address, and the PD phases they are most applicable to. Finally, Table 9 summarizes some of the solutions that help address the research questions. Research detailed in Chapter 3 shows how co-creating systematic sustainable design processes to aid the application of appropriate strategies helps lead to retention and long-term sustainable outcomes.

Table 9: Insights organized by research questions guiding the Synapse case study

Research Question	Insights
(RQ1) Receptivity to integration: What factors drive the company's receptivity to incorporating various SDMTs into their PD practice?	Senior leadership's enthusiasm
	Growing client interest
	Employees' personal passions
	Use of a structured learning approach
	Minimizing uncertainties in time & effort needed to engage in sustainable design
	Incorporating sustainable design into their culture and regular workflow
(RQ2) Valued tools: What do practitioners value in existing SDMTs?	Flexibility to use specific activities/mindsets from various methods and tools
	Ability select the right strategy for the problem at hand
	Structured approaches to aid application of strategies
	Addressing environmental, social and economic factors
(RQ3) Co-creation: How does the process of co-creating a customized sustainable design framework enable its integration into the company's PD practice?	Helped identify SDMTs most relevant to their context
	Helped align the framework with the dynamic and iterative nature of PD
	Helped gather insights from employees from various divisions and backgrounds
	Helped participants build ownership towards and want to champion the framework they created
(RQ4) Long-term impacts: How does the framework support continued consideration of sustainability in the company's PD practice over time — or if it fails to do so, why?	Communicating the value of sustainable design both internally and externally
	Helping clients identify their sustainability priorities
	Publishing case studies on how the framework helped enable the sustainable design transition

Case study conducted at SBD

The case study at SBD was conducted during my time there as an intern over two summers allowing me to conduct a longitudinal study. Internally, at SBD, three business units B1, B2, and B3 engaged in the co-creation process to varying degrees. This helped me understand the correlation between co-creation and long-term retention of the co-created processes. Practitioners from B1 engaged in the complete co-creation process lasting three months, while B2 met with me to simplify and adapt B1's process. B3 on the other hand sought to borrow B1's process as is.

Data collection methods used in this case study included conducting interviews and group discussions with practitioners to get feedback. Documents and insights gathered from the step-by-step co-creation process, detailed in Figure 27, were another key source of user input. I also analyzed existing documentation produced by SBD's CSR team on existing sustainability interventions and resources.

The resulting sustainable design process consisted of 42 mindsets and 7 activities extracted from a variety of existing SDMTs, that were added to the milestone PD process as shown in Figure 30.

Qualitative analysis of the interview transcripts, discussion notes, and other documents revealed the following four themes as critical drivers of the organization's sustainability transformation: 1) investor interest in ESG, 2) grassroots initiatives led by concerned employees, 3) market competition and brand reputation, and 4) regulatory pressures.

Upon returning to the company the following year, I interviewed all the practitioners I had previously interacted with from B1, B2, and B3, to assess the level of retention, dissemination, and application in real-life projects. `I found this to be positively correlated with the level of engagement in the co-creation process, with B1 applying the process in a project at the time.

I joined the project team to support their application of the sustainable design process. The project context, the application process, and the resulting outcomes are detailed in Section 4.2.3. The switch from gas-powered fastening systems to battery-powered systems reduced emissions by over 90%, and implementing a circular supply chain further cut emissions by another 30% while being financially viable. Interesting takeaways from the overall case study are listed in Section 5.3, and a short summary of solutions to the research questions guiding this study are outlined in Table 10.

Table 10: Insights organized by research questions guiding SBD case study

Research Question	**Insights**
RQ1: What do practitioners value in existing SDMTs?	Practitioners preferred mindsets over activities given the already long list of tasks in the SBD milestone process
	Familiar formats such as the Pugh Matrix eased adoption
	Consumer-facing business, B2, preferred strategies that can be translated to eco-labels, certifications, or standards
	All practitioners valued the use of LCA to support data-driven decision-making
RQ2: Does the process of co-creating a sustainable design process enhance receptivity and long-term integration into practice?	Yes, level of engagement in co-creation was positively correlated to retention, one year later. Other factors driving receptivity include: 1) investor interest in ESG, 2) grassroots initiatives led by concerned employees, 3) market competition and brand reputation, and 4) regulatory pressures.
RQ3: How does a co-created sustainable design process lead to the development of more sustainable products and services?	The sustainable design process when applied in practice resulted in more sustainable outcomes.

The case studies at Synapse and SBD, conducted in two very distinct contexts, show how co-creating unique sustainable design processes/frameworks at organizations can lead to successful adoption, retention, and implementation. This thereby addresses Challenge #2 presented by the ecodesign paradox, which is that practitioners struggle to translate environmental impact information obtained from simplified LCAs into tangible, actionable design decisions that lead to sustainable outcomes. In both cases, the frameworks were successfully applied a year or more after the study, and have yielded products with lower impacts than the baseline concepts or competition.

Simplified LCA tools like EcoSketch coupled with unique sustainable design frameworks co-created with companies together help them get across the "ecodesign paradox" chasm towards sustainability transformation. However, new technological advances in artificial intelligence (AI) presents many new opportunities to further simplify the incorporation of sustainability considerations into PD. In the next section, I discuss how AI could optimize how LCAs are performed in practice.

5.2 Future opportunities for sustainable design research

The prior sections of the discussion serve as a reflection and distillation of key takeaways from my PhD research. I now conclude with more forward-looking thoughts on important opportunities for future work.

5.2.1 Opportunities at the intersection of AI and digital sustainability tools

While EcoSketch unlocks fundamental new ways to perform LCAs under uncertainty and earlier in the PD context, it is still based on conventional databases and modeling techniques. New technological developments specifically in artificial intelligence (AI) and machine learning (ML) hold potential to further amplify the integration of these digital tools into PD practice.

Specifically, the use of AI and ML can greatly enhance the speed and accuracy of impact assessments and enable more efficient and effective decision-making during PD. For instance, AI-powered tools trained on datasets of publicly available LCAs and EPDs of existing products, can be used to predict the impacts of a product concept before it is even prototyped, allowing designers to make informed decisions that minimize negative environmental impacts at a lower cost to the company. Emerging work includes examples of such application of ML algorithms to predict the impacts and energy consumption in the sugarcane and construction industries [91], [92] when performing LCAs.

The integration of AI and LCA has indeed been a rapidly growing area of research in recent years, and literature identifies several ways in which AI can enhance the accuracy and efficiency of LCA [93]. One way AI can aid LCA is by improving the accuracy of data inputs [94]. For example, AI can be used to automatically extract and categorize product information from large amounts of unstructured data, such as product specifications, bills of materials, and supplier information. This can greatly reduce the time and effort required of a practitioner to manually collect and input data into an LCA model, and help ensure that the model is based on accurate and up-to-date information.

Another way AI can enhance LCA is by enabling more comprehensive and accurate assessments of environmental impact. For example, AI can be used to identify and analyze complex relationships among different environmental impact categories, such as water usage and carbon emissions, which can be difficult to capture using traditional LCA methods [95].

Finally, AI can be used to optimize product designs to minimize environmental impact. For example, AI can be used to generate and analyze large numbers of design alternatives, and identify those that minimize environmental impact while still meeting functional and performance requirements [96]. This can enable more efficient and effective decision-making in sustainable product design, and help designers identify new and innovative ways to reduce environmental impact.

In the development of novel tools like EcoSketch, it is important to consider the implications of technologies like AI to boost functionality. This goes hand in hand with the digital transformations organizations are undergoing to improve data transparency for reporting across complex global supply chains. Having discussed the technological developments that have the potential to revolutionize digital sustainability tools, I next shift my attention to the *people* involved in these transitions.

5.2.2 Opportunities for change in industry and research sustainable design practices

More and more companies are adopting corporate sustainability practices in recent decades, and a majority of executives agree that having a sustainability strategy is vital to staying relevant and competitive [97]. In this section, I discuss key levers that corporate sustainability practitioners, like myself, can target in order to drive change. Specifically, I address four topics that have repeatedly emerged, in literature and my research, as critical strategies to pursue organizational change towards sustainability. They are described and elaborated upon in the following subsections.

Setting measurable sustainability targets and pursuing data-driven decision-making

By setting specific, measurable targets, companies can establish a clear direction for their sustainability initiatives, align stakeholders, and hold themselves accountable. Pursuing data-driven decision-making on sustainability enables organizations to identify and prioritize the most significant environmental impacts of their products and operations, track performance over time, and continuously improve their sustainability performance. Specifically at companies that engage in hardware product development and manufacturing, techniques like LCA can help identify hotspots and aid integration of sustainable design strategies to address these hotspots, as shown in this thesis.

It is important for sustainability experts within organizations to contextualize high-level sustainability targets into design and engineering requirements or KPIs for project teams to pursue. Communicating how their day-to-day decisions contribute to the corporate goals can help build enthusiasm, ownership, and a sense of responsibility among employees. Next, I talk about the role people play in the sustainability transition.

Collaboration and leveraging people as change agents

Sustainability is a complex and interdisciplinary issue that cannot be solved by any single department or individual. It requires a collaborative approach that involves employees from across the organization, as well as external stakeholders such as suppliers, customers, and investors. One way to facilitate this dialogue is through the formation of cross-functional teams that bring together employees from different departments to work on sustainability initiatives. These teams can help break down silos and encourage sharing of knowledge and best practices, leading to more holistic sustainability strategies informed by a diverse set of stakeholders' perspectives [98]. I observed the formation of such a cross-functional team at SBD where employees that cared deeply about sustainability got together to launch initiatives such as creating a sustainable materials database, discussed in Section 4.2.2. This leads us to the question of leveraging the different roles that different employees play in acting as sustainability champions.

Prior work identifies four such ways in which employees act as change agents in the sustainability transition: 1) expert, 2) facilitator, 3) catalyst, and 4) activist [99]. An expert, as the term suggests, focuses on contributing their technical excellence gained through specialization. Experts are great problem solvers. A facilitator focuses on people development by creating opportunities for knowledge sharing, and working to change attitudes. A facilitator helps build teams. A catalyst on the other hand is associated with initiating change, providing strategic direction, and influencing leadership. Catalysts have an eye for the big picture. Finally, activists are motivated by fighting for a cause and leaving behind a legacy of improved conditions. Activists help bring urgency and accountability to the process. It is important to identify employees from across the company with an affinity for one or more of these roles, and an interest in sustainability, and bring them together in cross-functional teams to drive change. While this section addresses internal company dynamics, there are powerful external forces that also have a role to play in driving sustainability.

Creating a compelling sustainability story for investors and customers

Investors and customers alongside regulatory pressures form critical external forces that drive a company's sustainability transition. While prior work, discussed in Sec 1.4, shows that a growing number of investors are incorporating ESG performance into their investment decisions, there are many holdouts. Communicating sustainability performance to win over investors and customers, without greenwashing, is a delicate task [100]. Successful sustainability communication establishes authenticity and credibility by clearly outlining genuine motivations, transparently tracking progress, and providing tangible evidence of real-world impact. Setting a clear moral gist or aim, choosing relatable characters that the audience (be it leadership, employees, investors, or customers) can empathize with in an aspirational story structure, and sharing the story on the right media platforms, can go a long way in influencing investor and consumer decisions. Compelling sustainability stories can also serve as a powerful tool to inspire employees and galvanize support around the cause, potentially leading to big business model changes like the ones described below.

Pursuing business model innovation

Business model innovation is a key lever for companies looking to achieve sustainability. Sustainable business models incorporate sustainability as an integral part of the company's value proposition and value creation by going beyond delivering economic value. This involves exploring new revenue streams, partnerships, and business practices that drive value for both the company and society as a whole. One such approach involves adopting circular economy principles.

In a circular economy, the focus is on designing out waste and pollution by keeping products and materials in use, and regenerating natural systems. This approach presents opportunities for companies to rethink their supply chains to reduce environmental impacts and resource depletion. An example of piloting a circular supply chain was detailed in Sec 4.2.3, where fastening tools were remanufactured by retaining resource intensive components like the battery and electronics. This led to a significant reduction in impacts from the materials and manufacturing phase of the product's life cycle. In addition to environmental benefits, these business models are capable of reducing expenses related to extended producer responsibility (EPR) regulations and carbon tax legislations that may soon be a reality worldwide.

However, circular business models require a shift away from traditional linear models of production and consumption, which can require significant changes in business processes, supply chain relationships, and customer behavior. First, products need to be designed with end-of-life considerations in mind, such as the ability to be disassembled, repaired, remanufactured, or recycled. Another challenge is the complexity of reverse logistics. Companies must first find ways to incentivize customers to return their products at the end of their useful life. Following this, they may need to develop new infrastructure such as recycling facilities and collection networks to ensure that materials are collected, sorted, and processed efficiently.

Despite these challenges, there is a need for companies to adopt sustainable business models like circularity to achieve global and corporate climate targets. The benefits of adopting such models, including reduced waste and resource consumption, cost savings through avoiding EPR and carbon tax expenses, as well as improved brand reputation, make the shift to sustainable models of business an essential strategy for the future.

Chapter 6. Conclusion

Environmental issues such as extreme weather events caused by climate change, resource depletion, and rising pollution have heightened industry focus on sustainability. For companies that design and manufacture hardware products, it has become critical to consider the environmental impacts of their products throughout the product life cycle from material sourcing to end-of-life.

My research enables companies to systematically integrate sustainability considerations into the early stages of product development when critical decisions are made. To ensure these decisions are data-driven, I designed and developed a simplified life cycle assessment tool, "EcoSketch", tailored to the needs of designers and engineers who are engaged in product development but not necessarily LCA experts. The development of EcoSketch was motivated by a study I conducted that involved needfinding with such practitioners as well as audits of existing LCA software, which showed that such tools do not fulfill critical needs in the early stages of PD, like working with uncertain input data to produce estimates of impacts. My later evaluation study of EcoSketch verified that the tool's ability to account for such uncertainties allowed for a renewed workflow that significantly cut the time to perform LCAs - a major benefit for its adoption and application in the fast-paced PD context. However, access to better tools is only one piece of the puzzle. My literature review and interactions with PD practitioners showed that they additionally need support translating LCA results into actionable decisions through the selection of appropriate sustainable design methods and tools.

Through internships and longitudinal collaborations with industry partners such as Synapse Product Development and Stanley Black & Decker, I identified critical barriers and enablers to this adoption. Insights gained through qualitative research methods, including interviews and focus group discussions, informed the co-creation of a sustainable design process framework that can be applied on a variety of projects. Both frameworks incorporate the iterative application of simplified LCA throughout the PD process to guide decisions, thereby continually improving the sustainability of products. My longitudinal interactions with these companies showed their engagement in co-creating the frameworks was positively correlated to successful long-term retention and application of these frameworks. Further, several PD case examples at Synapse and SBD show how these processes directly resulted in significant reductions in environmental impacts.

In conclusion, I hope that my thesis provides direction to sustainability researchers and professionals seeking to pursue an organizational shift towards sustainability. Further, my work on EcoSketch provides a foundational example for successful collaborations between HCI researchers and sustainability practitioners to make better digital sustainability tools for industry. Ultimately this research seeks to contribute to a more sustainable future by empowering practitioners to create products that have a positive impact on both society and the environment.

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Appendix

Table A1. Characteristics of Synapse employees involved in our case study, including their current role at Synapse as well as educational and employment experiences

Partic-ipant	Current role at Synapse	Education	Total work experience, both at Synapse and prior
P1	Firmware Engineer (FE)	B.S.E in Computer Engineering (CE) and an M.S.E in EE	4 yrs FE
P2	Electrical Engineer (EE)	B.S. and M.S. in EE	4 yrs EE
P3	NPI Engineer	B.S. in ME	4 yrs ME/NPI
P4	Mechanical Engineer (ME)	B.S. in ME	5 yrs ME
P5	Project Manager (PM)	B.S. in Chemical Engineering (CE)	6 yrs CE, 6 yrs PM
P6	Senior Mechanical Engineer	B.A., M.Eng. in ME	8 yrs ME
P7	Principal Consultant (Systems Thinking and Circular Economy)	M.Eng. in ME	8 yrs Consultant
P8	Director of Mechanical Engineering	B.S. in ME	15 yrs ME
P9	Principal Strategy and Innovation Consultant	Ph.D. in Chemical Biology	15 yrs Consultant
P10	Senior NPI Engineer	B.S. in ME	21 yrs Mfg.E

Table A2. Grouping of sustainable design strategies by the sustainability focus areas they address, along with the triple bottom line

Focus Area	Triple Bottom Line			Sustainable design strategies across product life cycle stages
	Env.	**Social**	**Econ.**	
Resource efficiency	x			Avoid materials and processes that deplete natural resources
	x		x	Identify material and energy efficient manufacturing processes
Resource consumption	x		x	Design for improved durability and longevity
	x			Design for easy serviceability
	x		x	Minimize materials & energy consumed by the

				product during its use
Selection of low impact materials	x			Avoid conflict minerals
	x	x		Avoid toxic materials that damage human or ecological health in manufacturing, packaging, and end of life
	x			Identify materials with lower environmental impacts through manufacturing, packaging and end-of-life
Health and Safety		x		Mitigate health and safety risks of end-of-life strategy
		x		Ensure that failure modes and the associated health and safety risks are identified, mitigated and communicated
		x		Identify and communicate health and safety risks to all stakeholders in the distribution network
Social and Ethical Considerations		x		Inquire about the social and ethical considerations that apply to the client's distribution network
	x	x		Identify, comply with, and exceed social sustainability standards that apply to the system and supply chain
		x		Design to amplify positive social and behavioral impacts and minimize negative impacts from the product's use
Lowering negative impacts of waste	x		x	Manage, mitigate and find uses for waste from manufacturing and packaging
	x			Mitigate impact of waste during system use
Optimization of end-of-life	x		x	Design for easy disassembly
	x			Design for reuse, remanufacturing, and/or recycling
	x			Select end of life strategy based on relative environmental impacts
	x		x	Plan distribution and processing infrastructure to support the chosen end-of-life strategy
Transport and logistics	x		x	Optimize facility planning and distribution strategies for environmental & economic factors
	x			Optimize packaging strategy to minimize

				environmental impact of distribution
Economic efficiency and profitability			**x**	

Table A3: Full list of constituent activities and mindsets from SDMTs covered in the workshops

Sustainable Design Methodology	**Sub-categories**	**Constituent strategies**	**Activity / Mindset**
Lunar Field Guide	What is it trying to accomplish?	Question the premise of the design	A
		Reduce complexity	M
		Improve versatility	M
	How is it brought to life?	Reduce material variety	M
		Avoid toxic or harmful materials and chemicals	A
		Reduce size and weight	M
		Optimize manufacturing processes	M
		Design packaging in parallel with products	M
	How is it used?	Design for upgradeability	M
		Create durable and high quality designs	M
		Design for life after death	M
	Where does it end up?	Make it modular	M
		Maximize recycled, recyclable, renewable, and biodegradable materials	A
		Minimize fasteners	A
		Don't use paint	A
Circular Design Guide	Understand	Understand circular flows	A
		Regenerative thinking	M
		Service flip	M
		Insides out	M
		Inspiration: digital systems	M
		Learn from nature	M

	Define	Define your challenge	A
		Find circular opportunities	A
		Building teams	M
		Circular buy-in	M
		Circular business models	M
		Create brand promise	M
	Make	User-centered research	M
		Circular brainstorming	A
		Embed feedback mechanisms	A
		Smart material choices	M
		Concept selection	A
		Rapid prototyping	A
	Release	Product journey mapping	A
		Launch to learn	A
		Imagine new partnerships	M
		Create your narrative	A
		Align your organization	A
		Continuous learning loops	M
Okala Ecodesign Practitioner	Innovation	Rethink how to provide the benefit	A
		Provide needs provided by associated products	A
		Enable sharing of product by many people	A
		Anticipate technological change and build in flexibility	A
		Design to mimic nature	M
		Use living organisms in product	M
	Low impact materials	Avoid materials that damage human health, ecological health, or deplete resources	M
		Use minimal materials	M
		Use renewable resources	M
		Use waste byproducts	M
		Use thoroughly tested materials	M

	Optimized manufacturing	Design for ease of production quality control	M
		Minimize manufacturing waste	M
		Minimize energy in production	M
		Minimize number of production methods and operations	M
		Minimize number of parts/materials	M
	Efficient distribution	Reduce product and packaging weight	M
		Use reusable or recyclable packaging	M
		Use an efficient transport system	M
		Use local production and assembly	M
	Low impact use	Minimize emissions / integrate cleaner or renewable energy sources	M
		Reduce energy inefficiencies	M
		Reduce water use inefficiencies	M
		Reduce material use inefficiencies	M
	Optimized lifetime	Build in desire for long term product care	A
		Design easy product take-back programs	A
		Build in durability	M
		Design for maintenance and easy repair	M
		Design for upgrades	M
		Design second life with other function	M
	Optimized end-of-life	Integrate methods for product collection	A
		Provide for ease of disassembly	M
		Provide for recycling or downcycling	M
		Design reuse, or "next life of product"	M
		Provide for reuse of components	M
		Provide ability to biodegrade	M
		Provide for safe disposal	M
Synapse sustainable design guide	Materials and manufacturing	Avoid or reduce materials and processes that deplete natural resources	M

		Identify, comply with, and exceed social sustainability standards that apply to the system and supply chain	A
		Avoid toxic materials that damage human or ecological health	M
		Avoid conflict materials	M
		Identify material and energy efficient manufacturing processes	M
		Manage, mitigate, and inf uses for waste from manufacturing processes	A
	Distribution	Inquire about social and ethical considerations that apply to the client's distribution network	A
		Optimize facility planning and distribution strategies for environmental and economic factors	A
		Optimize packaging strategy to minimize environmental impacts of distribution	M
		Identify and communicate health and safety risks to all stakeholders in the distribution network	M
	Use and Maintenance	Design to ampify positive social and behavioral impacts and minimize negative impacts from products' use	M
		Minimize materials and energy consumed by the system during its use	M
		Design for improved durability and longevity	M
		Design for easy serviceability	M
		Mitigate impacts of waste during system use	M
		Identify and communicate possible modes of failure as well as health and safety risks	M
	End of life	Select end of life strategy based on relative environmental impacts	A
		Design for easy disassembly	M
		Design for reuse, remanufacturing, and recycling	M

		Plan distribution and processing infrastructure to support the chosen end-of-life strategy	A
		Mitigate health and safety risks of the chosen end-of-life strategy	M
Cradle-to-Cradle certification	Materials	All material ingredients identified (down to 100 ppm)	A
		All material ingredients defined as biological nutrient (BN) or technical nutrient (TN)	M
		Does not contain any Banned List substances	M
		Materials assessed for their intended use and impact on Human/Environmental Health according tothe following criteria: - Human Health: Carcinogenicity, Endocrine Disruption, Mutagenicity, Reproductive Toxicity, Teratogenicity, Acute Toxicity, Chronic Toxicity, Irritation, Sensitization - Environmental Health: Fish Toxicity, Algae Toxicity, Daphnia Toxicity, Persistence/Biodegradation, Bioaccumulation, Ozone Depletion/Climatic Relevance - Material Class Criteria: Content of Organohalogens, Content of Heavy Metals	M
		≥ 75% (by weight) of ingredients assessed, and any scoring "X" in assessment have strategy to phase out	M
		≥ 95% (by weight) of ingredients assessed (Or, for entirely BN products, 100%), and none have "X" assessment	M
		100% (by weight) of ingredients assessed, and none have "X" assessment	M
		Meets Cradle to Cradle emission standards	M
		All process chemicals also assessed, and none have "X" assessment	M
	Material reutilization	[see Materials point "All material ingredients defined as biological nutrient (BN) or technical nutrient (TN)"]	M

	/ design for environment	Material Reutilization Score ≥ 35	M
		Material Reutilization Score ≥ 50	M
		Material Reutilization Score ≥ 65	M
		Material Reutilization Score = 100	M
		Have “nutrient management” strategy for the product including scope, timeline, and budget	M
		Product is actively being recovered and cycled in a technical or biological metabolism	A
	Energy	Quantified energy use and source(s) for final stage of product manufacture/assembly	A
		Developed strategy for using renewable energy & managing carbon	M
		≥ 5% of electricity for final mfg stage is renewaby sourced or offset with Renewable Energy Credits, and ≥ 5% of direct on-site emissions are offset	M
		≥ 50% of electricity for final mfg stage is renewaby sourced or offset with Renewable Energy Credits, and ≥ 50% of direct on-site emissions are offset	M
		> 100% of electricity for final mfg stage is renewaby sourced or offset with Renewable Energy Credits, and > 100% of direct on-site emissions are offset	M
		Embodied energy is quantified (amount & sources), and strategy developed to optimize	M
		≥ 5% of embodied energy covered by offsets or otherwise addressed	M
	Water	Created or adopted water stewardship principles/guidelines	A
		Haven't violated discharge permit in last 2 years	M
		Determined if water scarcity or sensitive ecosystems are issues around their factories	M
		Facility-wide water audit	M

		Assessed all process chemicals in effluent OR Characterized ≥ 20% of Tier 1 suppliers' chemical effluent and water depletion.	M
		No problematic process chemicals in effluent (either removed from process or recycled to not enter effluent) OR Demonstrated progress on Tier 1 suppliers strategy from "Silver" level	M
		All water leaving manufacturing facility meets drinking water quality standards	M
	Social responsibility	Streamlined self-audit performed to assess protection of fundamental human rights	M
		Management procedures developed to fix any problems found in self-audit	M
		Full social responsibility self-audit performed & positive-impact strategy developed	M
		Performed material-specific and/or issue-related audit relevant to ≥ 25% of product material (by weight), e.g. FSC Certified, Fair Trade, etc. OR Supply chain social issues are fully investigated & positive-impact strategy developed. OR Company is actively conducting an innovative social project that positively impacts employee's lives, the local community, global community, social aspects of supply chain, or recycling/reuse.	M
		2 of the 3 "Silver" requirements done	M
		All 3 "Silver" requirements done	M
		Acceptable third party social responsibility assessment, accreditation, or certification	M

Table A4: Separate tables of strategies compiled by each of the five participants during the independent brainstorming step detailed in Sec 4.2.1.

Table A4.1: Strategies compiled by Participant 1

List of strategies
LCA material calculator score (vs. other material options)
Transportation method with carbon score (vs. baseline - can it be improved?)
Useful life plan (# of cycles scored vs. baseline)
Serviceability (modular design, recyclability of spare parts, can useful life be extended)
Upgradeability (can product be upgraded vs. replaced)
End of life management
commonize materials for easy recyclability
don't use painted materials
Implementation of recycling marks per EP139
Product with purpose score (what sustainable development goals are served)
Adherence to ES100118
Use of cadmium/lead free solder
Use of bromide free resins and compliance of colorants
Use of cadmium/lead free solder
Implementation of vendor compliance audits
Material audit of high risk materials per EP154
Packaging design (optimize material, eco-friendly - score vs baseline)
End user impact (carbon footprint during useful life vs. baseline); battery life, power consumption, etc
Material usage by weight (vs. baseline - can it be reduced?)
Manufacturing carbon footprint (can it be measured?)
Can a services revenue model be applied (licensing, repair, end of life management, etc.)
Ecosmart submission

Table A4.2 Strategies compiled by Participant 2

Groups	Strategies
Miscellaneous	Design for serviceability
	ES100118 check
	Plastic component recyclability
Specifications	Design intent - multiple uses
	Complexity - quantity of components
Materials	Identification of toxic/harmful materials
	Reduce size and weight
	Minimize machining processes
	Use low energy manufacturing processes
	Sustainable packaging decisions
Use	Upgradability
	Serviceability - repair components
End-of-life	Reuse / repurpose
	Recycle rare earth metals

Table A4.3 Strategies compiled by Participant 3

Groups	Strategies
Product Life	Increase durability
	Increase quality to extend product life
	Design for easy serviceability & upgrade
	Tools should not be low quality/ throw-away
	Reduce consumable / wear items
Product Weight	Weight reduction - reduced transport emissions
Capability	Increase tool capability
	Can be used with multiple fastener types & sizes
	1 tool suits many applications
Commonality Level	Maximize commonality of parts used across multiple tools
Complexity	Reduce part count / product complexity

Modular design	Easy upgrade/conversion for multiple application types
	Easy repair & servicing
	Easier to recycle
Product Life Cycle	Use innovation/technology to increase market life
	Upgradeable
	Modularity
	Future proof design
Power Source	Use sustainable power source
	Compressed air vs hydraulic vs battery
Product Size	Reduce size/weight - reduce shipping impact
	Reduce size - reduce packaging volume
Material	Increase use of sustainable materials
	Increase use of recyclable materials
	Increase use of lightweight materials
	Reduce variety of materials
	Avoid use of harmful / toxic materials
Efficiency	Improve tool efficiency to reduce power consumption
Capability	Maximize capability to reduce product range - 1 size suits all
Component Design	Optimize geometry to reduce waste in manufacture
	Optimize use of low energy manufacturing processes
	Minimize variety of manufacturing processes
	Minimize use of harmful processes - HT / Plating / Cleaning / coatings / paint
	Review effect of sub-assembly vs 1-piece to reduce waste/harmful materials
	Optimize commonality of parts with other products
Tool Assembly	Modular design
	Reduce complexity for easy assembly and servicing
	Reduce number of fasteners required
	Minimize need for energy consuming assembly processes
	Use off-the-shelf readily available parts where possible

	Minimize use of chemicals/adhesives/lubricants etc
Packaging	Minimize volume of packaging required
	Maximize use of sustainable / recyclable materials
	Reusable packing - packaging return/reuse scheme
Prototyping	Minimize quantity of prototypes required to validate design
	Manufacture prototype via final production method to reduce no. of iterations required
DV Testing	Use FEA / Simulated testing where possible
	Incorporate HALT testing to reduce prototyping qty & test duration
	Incorporate Taguchi / Design of Experiments to optimize DV tests
	Minimize energy/resource consuming test methods ie. fastener placing / compressed air supply
Durability	Optimizing product durability
Location	Reduce number of manufacturing and assembly plants required
	Reduce distance between manufacturing locations and Distribution Centres
	Manufacture/assemble in multiple countries to reduce shipping
Processes	Reduce number of manufacturing processes
	Minimize use of harmful processes - HT / Plating / Cleaning / coatings / paint
	Minimize use of harmful processes - HT / Plating / Cleaning / coatings / paint
	Review casting / molding vs machining

Table A4.4 Strategies compiled by Participant 4

Stages	**Strategies**
MS 0/1	Increase use of recycled, recyclable, renewable, or biodegradable materials where possible
	Design for increased product lifetime (durability), serviceability, and upgradability
	Design for recyclability, reuse, and/or remanufacturing
	Minimize materials and energy consumed by the product during its use

MS 2	Minimize material and energy use during manufacturing
	Review suppliers' environmental and social sustainability standards
MS 4	Minimize environmental impacts of packaging materials and processes
	Optimize facility planning and distribution strategies for environmental and economic factors
	Plan distribution and processing infrastructure to support chosen end-of-life strategy

Table A4.5 Strategies compiled by Participant 5

Participant 5	
Stages	**Strategies**
MS 2	Selection of materials that are not energy-intensive and easily recyclable
	Eliminate unnecessary fasteners by using other processes (welding)
	Make tool easily rebuildable
	Make wear components easily accessible and replaceable
	Minimize tool energy usage
	Use recycleable, non-polluting lubricants
	Add corrosion resistant coatings
	Design for modularity and easy of upgrade
	Increase tool versatility when possible
	Use existing components when possible
	Design for 3D printing for low volumes vs machining
	Use FEA to eliminate excess materials
	Add lubrication containment means, to avoid leakages
	Reduce packaging materials

Table A5: Filled out Pugh Matrix based on the case study detailed in Sec 3.3

LCA Stages					Design-for-Sustainability Strategies	(0-5)	DATUM	C1	C2
Mtls.	Mfg.	Dist.	Use	E-o-L					
					Product Life				
X	X	X	X	X	Design for durability	3		+	+
X	X	X	X	X	Design for upgradeability	3		s	s
X	X	X	X	X	Design for serviceability and modularity	3		+	+
					Add coatings to improve durability (corrosion resistant, wear resistant, etc.)	3		+	+
X	X	X	X	X	Improve product quality	3		s	s
					Product versatility				
X	X				Increase tool capability - ability to use the same tool for multiple purposes	3		-	-
					Tool complexity				
X	X				Reduce material variety	3		-	-
X	X				Maximize commonality of parts across tools	3		-	-
X	X				Reduce part count where possible	3		-	-
X	X				Use off-the-shelf parts and existing components where possible	3		s	s
X	X				Reduce tool weight and size	3		-	s
X	X				Compare the impacts of creating multiple sub-assemblies vs using a single part	3		s	s
					Sustainable materials				
X					Increase the use of recycled, recyclable, renewable, or biodegradable materials	3		-	-
X					Avoid the use of toxic or harmful materials (Check ES100118 restricted materials survey & conflict minerals survey)	3		s	s
X					Measure and compare the environmental impacts of material choices using LCA	3		-	-
					Resources consumed during manufacturing				

					Avoid surface finishing when not needed	3		+	+
	X				Use FEA/simulated testing instead of hardware prototyping where possible	3		s	+
	X				Use HALT testing to reduce prototype quantity and testing duration	3			
	X				Use less energy and/or energy from sustainable sources for manufacturing	3		-	-
	X				Reduce overall environmental impacts of manufacturing	3		-	-
	X				Optimize part geometry and manufacturing processes to minimize waste	3		-	-
	X				Minimize variety of manufacturing processes	3		s	s
					Resources consumed during use				
			X		Reduce consumables used	3		+	+
			X		Improve tool's energy efficiency (impacts of compressed air vs hydraulic vs battery operated)	3		+	+
			X		Implement lubrication containment to reduce quantity of lubricants used	3		+	+
			X		Electricity Calculation - kg CO2e per kWh	3		+	+
					Optimize packaging				
X	**X**	**X**			Reduce packaging volume per tool	3		s	s
X	**X**	**X**			Reduce number of packaging materials used	3		s	s
X	**X**	**X**			Consider using reusable packaging that can be collected back	3		s	s
					End of life management				
				X	Design for recyclability, reuse, or remanufacturing	3		+	+
				X	Plan logistics and processing infrastructure to support chosen end-of-life approach	3		s	s
		X			**Emissions from distribution**				
		X			Manufacture / assemble locally	3		+	+

		X			Compare carbon emissions of chosen transportation mode against a baseline	3		+	+
					Compliance				
X					Check adherence to ES100118	3		s	s
X					Ensure that Product w/ Purpose social and environmental goals are considered	3		s	s
X					Ensure plastic recycling labeling per EP139	3		s	s
X					Audit high-risk materials per EP154	3		s	s
					Supplier Sustainability				
X	X	X	X	X	Completion of Code of Conduct survey	3			
X	X	X	X	X	Completion of Carbon Disclosure Project survey	3			
X	X	X	X	X	3rd Party Social Accountability Certification, especially for finished goods manufacturers	3			
X	X	X	X	X	Supplier has set Scope 1 and Scope 2 Science-based Targets - supports our goal of ensuring 2/3rds of our supply chain has set science-based targets	3			
	X				Supplier can provide company-specific emissions data for products/services provided	3			
					S+		**0**	**33**	**36**
					S-			30	27
					SS			48	48
					Total			**3**	**9**

Table A6: Bill of Materials listing parts and sub-assemblies per battery-powered fastener (excluding the battery). Masses indicated as "-" or "0" refer to either missing data or data already accounted for respectively.

Description	Sub-Assembly	Quantity per tool	Mass (kg)
NOSE HOUSING	Housing Assy	1	0.68
MAST HOUSING	Housing Assy	1	0.281
NOSE RETAINER	Housing Assy	1	0.0839
IDLER GEAR PIN	Housing Assy	1	0.037
HOUSING	Housing Assy	1	0.728
REAR THRUST BEARING SPACER	Housing Assy	1	0.01
THRUST BEARING ASSEMBLY	Housing Assy	1	0.25
FRONT MOTOR BEARING SUPPORT	Housing Assy	1	0.015
O-RING	Housing Assy	1	0.001
PHA SEAL HALLITE 4704500	Housing Assy	1	0.003
RETAINING CLIP	Housing Assy	1	0.003
PLANETARY OUTPUT SHAFT BEARING	Housing Assy	2	0.008
NEEDLE BEARING	Housing Assy	2	0.156
THRUST WASHER	Housing Assy	1	0.043
THRUST BEARING	Housing Assy	1	-
THRUST WASHER	Housing Assy	1	0.012
PLANETARY RETAINER CLIP	Housing Assy	1	0.01
KEY FOR PLANETARY RING GEAR	Housing Assy	1	0.0001
IDLER GEAR	Housing Assy	1	0.045
IDLER GEAR BEARING	Housing Assy	1	0.009
THRUST WASHER	Housing Assy	3	0.01
MOTOR OUTPUT ADAPTOR	Gear Box	1	0.028
RING GEAR REWORK	Gear Box	1	0
SPIDER ASM EB G4, 16T, 15TP	Gear Box	1	0
RING GEAR BASE	Gear Box	1	0
PLANETARY ASSEMBLY	Gear Box	1	0
OUTPUT PLANETARY CARRIER	Gear Box	1	0
PIN	Gear Box	4	0
PLANET GEAR	Gear Box	4	0
NEEDLES	Gear Box	56	0
THRUST WASHER	Gear Box	3	0
CARRIER	Gear Box	1	0

PIN	Gear Box	3	0
PLANET GEAR	Gear Box	3	0
NEEDLES	Gear Box	42	0
CLIP	Gear Box	1	0
GEAR	Roller Screw Assy	1	0.148
TAIL	Roller Screw Assy	1	0.013
SPRING PLUNGER	Roller Screw Assy	1	0.005
MAGNET	Roller Screw Assy	1	0.001
SCREW	Roller Screw Assy	2	-
ROLLER SCREW	Roller Screw Assy	1	1.39
ANTI-ROTATION KEY	Roller Screw Assy	2	0.007
TAIL MOUNT	Roller Screw Assy	1	-
LOCKING NUT	Roller Screw Assy	1	0.0116
REWORKED MOTOR ROTOR	Motor Assy	1	0.089
CIRCLIP	Motor Assy	1	0.004
MOTOR FAN SHROUD	Motor Assy	1	0.038
SA ROTOR BLDC ALLIGATOR	Motor Assy	1	0.45
SA STATOR AND CAN BLDC ALLIGATOR	Motor Assy	1	0.45
FAN	Motor Assy	1	0.1
BEARING, BALL	Motor Assy	1	0.01
SCREW	Motor Assy	4	0.001
CIRCLIP	Motor Assy	1	0.001
SENSOR BOARD ASSEMBLY	Electronic Assy	1	0.05
Battery - 9.0Ah	Electronic Assy	1	1.043
CONTROLLER BOARD	Electronic Assy	1	0.05
SA PCB & WIRES PWR HIP6, BGV	Electronic Assy	1	0.15
DISPLAY BOARD	Electronic Assy	1	0.05
HANDLE RIGHT, COVER	Mechanical Assy	1	0.25
HANDLE LEFT, ASSY	Mechanical Assy	1	0.25
SCREEN LABEL	Mechanical Assy	1	-
SCREEN PLATE	Mechanical Assy	1	-
SCREEN BUTTON	Mechanical Assy	1	-
TAPTITE TORX SCREW	Mechanical Assy	10	0.01
COLLET	NE	1	0.15
12mm Anvil	NE	1	0.214

Figure A1: SBD's ESG evolution timeline

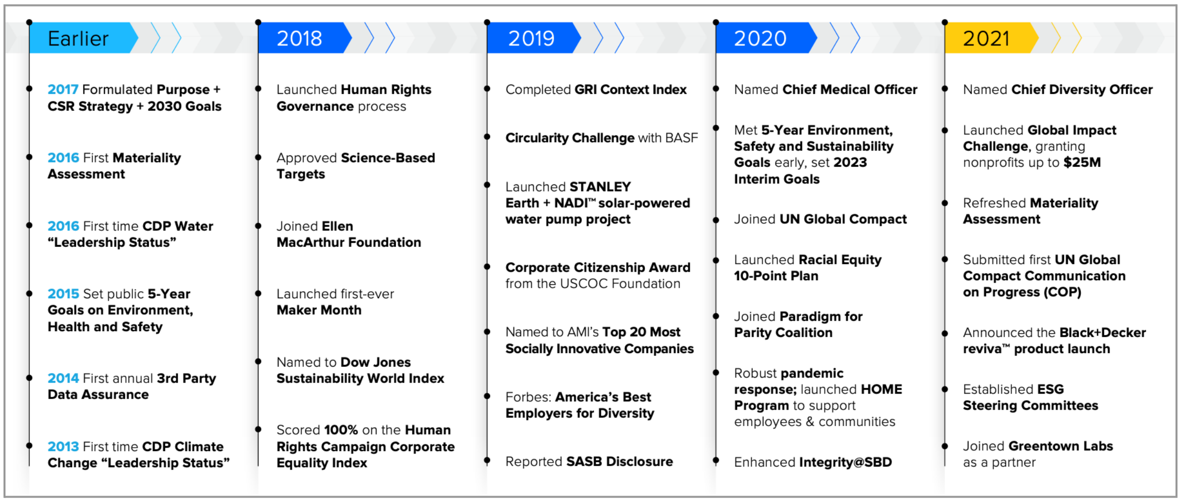

Figure A2 (1 - 8): Preliminary calculations to measure use phase environmental impacts of the gas-powered and battery-powered fastening systems

1 - Number of power tools and region under consideration:

Input the total number of tools for this comparison =	5	
Input region =	US	

2 - Energy consumption of power tools:

Hydraulic tools: AV20

Battery Tools: LB45PT-70 with 9 Ah battery

Calculate fasteners per charge =	500	fasteners per charge
Calculate peak energy use per charge =	108	Watts
Calculate charging time =	1.25	hours

3 - Calculate average tool operating time:

Input average free-run portion of operating time (free cycle & piston return) =	3.0	sec.
Input average clamp and broach portion of operating time =	1.0	sec.
Calculate average tool operating time per fastener =	4.0	sec.

4 - Calculate average number of fasteners per assembly operation:

Input number of tools used for 1 fastener per assembly =	-
Input number of tools used for 2 fasteners per assembly =	1
Input number of tools used for 3 fasteners per assembly =	1
Input number of tools used for 4 fasteners per assembly =	2
Input number of tools used for 5 fasteners per assembly =	1
Verify total number of tools =	5
Total number of fasteners per assembly =	18
Average number of fasteners per assembly operation =	3.6

5 - Calculate total production units per year:

Input number of production hours per day =	6	
Input number of production days per week =	6	
Input number of production weeks to build site =	18	
Calculate hours per tool =	648	hours
Calculate total tool hours =	3,240	hours
Calculate fasteners per hour =	78	
Calculate time per fastener =	46.2	seconds
Calculate number of production units per tool =	50,500	
Service life of AV20 tool =	250,000	cycles
Service life of LB45PT-70 tool =	300,000	cycles

6 - Assembly plant energy specifics:

Utility costs:

Enerpac Unit		
Input cost of electric energy per kilowatt-hour =	$ 0.08	per kWh
Pump Model =	ZE4	
Motor Power =	1.12	kW
Power Supply Voltage =	115.0	V
Average Current (assume 50% max) =	3.4	A
Calculate cost to run per production day =	$ 0.54	
Site Generator		
# Sites	1	
Solar capacity	50	MW
# generators	3	
Diesel Gallon Usage	2	per generator
Look up CO2 per gallon/gas	22	lbs
Diesel cost per Gallon	$ 5.61	(May 2022)
Calculate # Fasteners per site	252,500	
Grip 3 / 4 Fasteners per MW	2,000	Avbolt
Grip 6 Fasteners per MW	250	Avbolt
M12 Fasteners per MW	2,800	NeoBolt
kWh for 60V battery	0.162	
cycles / charge 6	333	6Ah Battery
cycles / charge 9	500	9Ah Battery
Site Towing Vehicle (ATV)		
Gallon Usage	5.4	per vehicle per day / ATV
Look up CO2 per gallon/gas	22	lbs

7 - Calculate energy consumption for assembly tools and Tow Vehicles

Annual energy cost to operate 5 AV20 hydraulic tools:

Calculate fasteners / site =		252,500	
# cycles per AV20 tool =		50,500	OK
Calculate gallons used for generators =		648	gallons / site
Calculate gallons used for Towing Vehicle =		1,750	gallons / site
Calculate cost of diesel =	$	13,460	/ site
Calculate total cost of energy to operate hydraulic tools with generators =	$	13,460	/ site

Annual energy cost to operate 5 LB45PT-70 battery tools:

Calculate fasteners / site =		252,500	
Fasteners per Ah =		56	
Calculate # charges =		505	
Electricity required to complete site build =		4,545	Ah / site
Calculate energy use per site =		736	kWh / site
Calculate total annual cost of energy to operate LB45PT-70 tools =	$	58.90	/site
Potential annual savings by selecting LB45PT-70 tools =	$	13,401	/ site
This represents		**99.6%**	**cost savings in energy consumption.**

8 - Calculate CO2 Production for Hydraulic Tooling:

Annual energy cost to operate 5 AV20 hydraulic tools:

Calculate cost of diesel =	$	13,460	/ site
Total fuel consumed for hydraulic tooling =		2,398	Gallons
Total CO2 produced for hydraulic tooling =		24.3	Tons CO2

Annual energy cost to operate 5 LB45PT-70 battery tools:

Calculate energy use for LB45PT-70 tooling =		736	kWh / site	
Average CO2 emissions related to total electricity production in your region =		681	grams per kWh	
Calculate CO2 produced for battery tooling =		0.6	Tons CO2	
Total carbon savings using battery tooling vs. hydraulic tooling =		23.8	Tons CO2	(Individual site CO2 savings)
How many sites are in your system =		120	(Savings for their complete project)	
Total Carbon savings if using all battery tooling =		2,854	Tons CO2	
Total energy savings if using all battery tooling system wide =	$	1,608,147		

Assumptions
- 1 generator for 2 tools
- ATV fuel capacity 5.4Gal
- 1 ATV per generator
- 1 tank per day per ATV