Article

Co-Creating a Framework to Integrate Sustainable Design into Product Development Practice: Case Study at an Engineering Consultancy Firm

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Abstract: There is a growing recognition of the need to incorporate sustainability considerations early-on in the product development (PD) process (PDP). As part of a case study at an engineering consultancy firm, this paper identifies considerations that influence the integration of sustainable design practices into real-world PD practices. This is informed by the first author getting embedded in the firm as an intern, and 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. From literature and observation, we find that designers and engineers often struggle to identify and apply the right sustainable design methods and tools (SDMTs) to tackle the environmental impacts associated with their products. Through a human-centered design process, we co-created a reusable, modular framework of practices that aids the selection of relevant strategies, based on the environmental hotspots, stage of the PD process, and the client's sustainability priorities. The paper further presents insights related to the framework's real-world application and impacts in the firm, based on results of longitudinal engagement with the firm.

Keywords: sustainable product development; sustainable design; product development practice; corporate sustainability practices

1. Introduction

1.1 Motivation and aims

Sustainable development has become an imperative topic of our time, gaining importance and public awareness since the hallmark Brundtland Report [1]. Product innovation is now seen as one strategy to address systemic mega-risks that pose unprecedented challenges to companies and governments, including environmental threats [2], making sustainability an important consideration in product development (PD). Academic researchers and practitioners alike have therefore developed numerous sustainable design methods and tools (SDMTs) in recent decades. Early forms of sustainable design [3]; [4] focused primarily on redesigning individual qualities of products, such as improving an item's recyclability. Recent efforts have expanded in scope to look more broadly at the socio-technical system level of PD [5]. However, industry practitioners often do not utilize SDMTs as whole methods, but rather mix and match parts of different methods opportunistically [6], just as they do with traditional design methods [7,8]. The framework created in this study accounts for such ad hoc approaches as well as other considerations identified from both established literature and our engagements with practitioners, thereby aiming to be applicable in practice at real-world companies.

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Design practices have been classified by PD stage [9], on a spectrum of qualitative checklists and rules of thumb to quantitative impact assessment techniques [10], or even by whether they consider environmental, social, and/or economic factors [11]. Terms such as "design for sustainability", "ecodesign", or "design for environment" are often used interchangeably to refer to sustainable product development [12]. Similarly, there is no universal consensus around terminology for the sustainable product development practices, but this paper uses the following definitions from [9]:

- An *"activity"* is something practitioners physically do (e.g., calculate, draw, etc.);
- A *"mindset"* is something practitioners mentally consider (e.g., a goal, paradigm, etc.);
- A *"tool"* is an object (physical or software) used to perform an activity and/or spur thought along a mindset;
- A *"method"* is an ordered set of activities with accompanying mindsets;
- A *"strategy"* is a mindset (or collection thereof) that may be accompanied by specific activities, or may be considered during normal design activities (e.g., brainstorming, cost estimation, etc.)
- A *"practice"* generically refers to any and all design methods, activities, mindsets, tools, or combinations thereof.
- A *"practitioner"* refers to designers, engineers, managers, or other stakeholders involved in industry product development decision-making and execution.

Further complicating matters, most practitioners lack training in sustainable design [13,14], and therefore struggle with both identifying the environmental effects of their products as well as selecting the right strategies to improve those impacts. The existence of a vast variety of methods, strategies, and tools makes these choices harder. Additionally, there is growing agreement about the need to incorporate sustainability considerations early-on in the PD process [15]. The early phases are rife with uncertainties, however, as critical decisions (e.g., about choice of materials, manufacturing processes, product architecture) have yet to be made [16].

Altogether, these challenges motivate the need for a modular, customizable, easy-to-use approach if sustainability considerations are to be realistically integrated. To address this problem, we undertook research in partnership with an engineering consultancy firm. Our case study aimed 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. Additionally, our human-centered design (HCD) approach to developing this framework placed our partner organization's context and needs at the center of the research. Specifically, the first author was embedded into the firm to understand the intricacies of their PDP. She conducted interviews, focus group sessions, and activities that helped co-create the novel framework. Beyond the framework itself, this paper also contributes insights regarding how this participatory approach can be more widely applied to offer generalizable utility for design researchers and practitioners seeking to implement their interventions in other organizational contexts.

1.1. Background and related work

Prior work indicates that practitioners need support identifying the right SDMTs for the job [13,14]. Both [17] identify that multi-step methods are often not applied as tunnels of process, but that practitioners opportunistically skip steps or combine elements from various methods and tools. Since these less disciplined processes are more efficient in time and resources [8], our framework mainly allows the selection of *"strategies"*, which are constituent activities and mindsets or a combination thereof, rather than whole *"methods"* [6]. The selection of strategies can be informed by the stage of PD process [18,19]; the life cycle stages they address [20–22]) or the need for a quantitative or qualitative approach [11,18,23].

[24] use "sustainability impact categories" (referred to as "focus areas" in this paper) based on the Design for Sustainability impact profile [25], the EcoDesign Checklist [26],

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and the Method for Sustainable Product Development [27] for their Checklist for Sustainable Product Development (CSPD). [24] asserts that this organization affords practitioners an additional lever to identify strategies based on sustainability priorities. The CSPD, however, only uses qualitative SDMTs and is tailored to the automotive industry context.

We argue that the use of simplified life cycle assessment (LCA) offers a light-weight, data-driven approach to select strategies based on the environmental impact hotspots identified, thereby maximizing benefit [16]. LCA is a method 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 [28,29]. However, [28] points out that LCAs performed early-on are impeded by limited knowledge of the product and other uncertainties despite holding the greatest potential for improvement. This paradox can be tackled through the use of lightweight simplified LCA tools tailored to the early-stage PD context [16] as well as an iterative application of LCA through the PD process to track the shrinking uncertainty as design decisions are made.

In this paper, we introduce a framework that guides users through the iterative selection and application of appropriate sustainable design strategies based on simplified LCA results, stage of the PD process, and other specific client priorities. A systematic literature review by [30] on ecodesign implementation identifies the organizational context as a critical factor. [31] highlights that the "soft side", or the "human side" [32], can make or break ecodesign implementation. A large-scale survey conducted by [33] identifies "management" as the biggest challenge to ecodesign implementation, closely followed by "collaboration", "strategy", and finally "tools" and "knowledge". Our human-centered approach combined participatory design [34] and co-creation [35] helped gain deeper insight into the human side through close observation, participation, interviews, and discussions, guiding the iterative design of the framework. Our study confirmed that closely involving the users in the design process enhances acceptance of the framework [36].

1.2. *Data collection procedures*

The development of our 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 paper 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 our longitudinal engagement;

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

- **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 2 presents our methods to engage with our case study PD firm. Section 3 discusses insights from interviews, focus groups, and other captured data, with findings organized by emergent themes around incorporating sustainable design into PD. Section 4 discusses how these insights were collaboratively translated into

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a modular sustainable design framework, and revisits how this work answers our guiding RQs. We conclude with how the firm continues to employ the framework, and future research opportunities unlocked.

2. Materials and methods

2.1. Participants and study context

The industry partner selected for this case study was Synapse Product Development Inc. (referred to hereafter 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 [37,38] 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 our 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 our 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.

The first author 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, the researcher 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 4 in the Appendix provides their full characteristics and anonymized identifiers.

2.2. Data collection procedures

The first author 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 R1 and R2. Later sessions involved presenting variations of the framework to gather feedback and iteratively make refinements. By being embedded at the firm as an intern, the researcher established rapport and trust with her colleagues so they could comfortably share both positive and negative feedback.

2.2.1. Interviews and focus groups

A total of 17 group discussions and four one-on-one semi-structured interviews with Synapse employees were conducted by the first author. Each session lasted an average of 45 minutes. Audio was recorded for transcription and analysis. In group discussions where recording was not possible, the first author 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

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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. The first author 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.

2.2.2. Project documentation

As part of our investigation into Synapse's PD practice, the first author obtained access to documentation on past and current projects to better understand the company's PDP conventions and project workflows. She 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 for RQ3.

2.2.3. Participatory development of the sustainable design framework

We took an HCD approach to co-create a framework putting users' needs first and paying particular attention to making our 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 not only helps provide deep insight into their needs, but also enhances the acceptance of the outcome [36], which we observed over the course of our longitudinal engagement following the initial study. The participatory, collaborative, and iterative process is depicted in Figure 1.

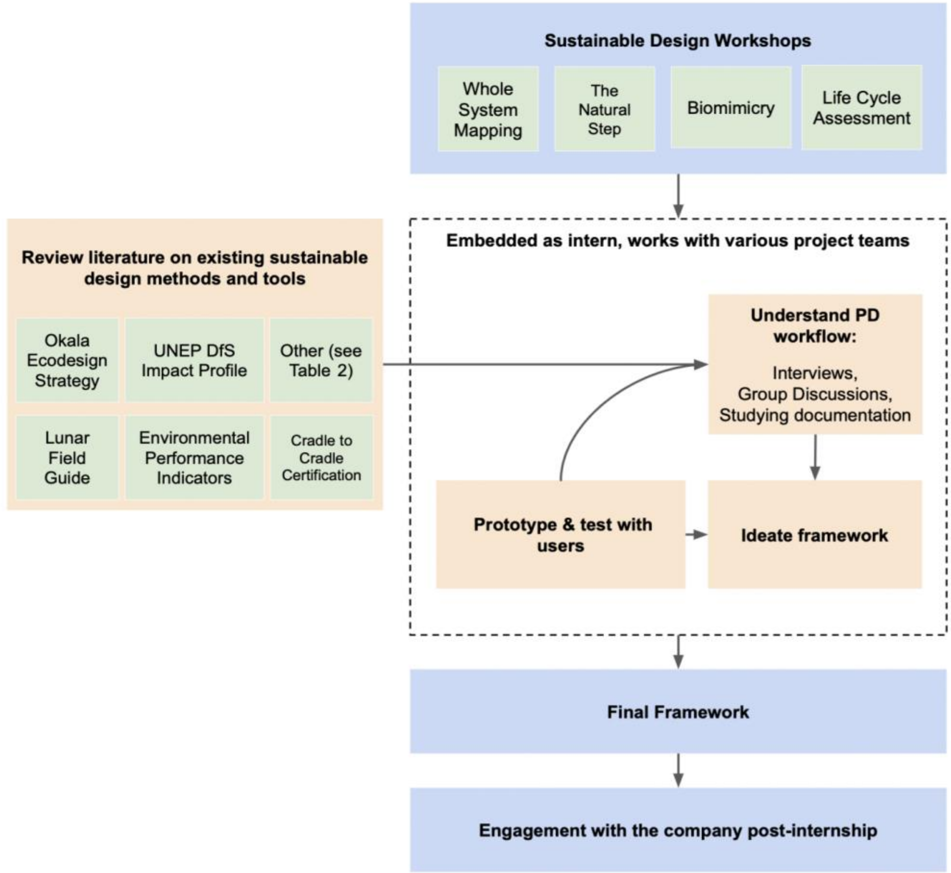

Figure 1. The participatory process applied to answer our research questions and co-create the sustainable design framework.

2.2.4. Ongoing engagement with the company post-internship

We continued to engage closely with our partner company following the conclusion of the first author's 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. 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 [39].

2.3. Qualitative data analysis

Interview transcripts and group discussion notes were qualitatively coded to identify patterns and extract insights [40]. The emergent themes describe key considerations we sought to address in the co-creation process. Table 1 in the Results section summarizes these high-level themes, together with sub-themes that reflect specific considerations.

3. 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 3.1, 3.2, 3.3, and 3.4 unpack the insights from the themes and sub-themes, organized by the research questions they address.

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Table 1. Themes and sub-themes that emerged from our qualitative analysis of interviews and focus group discussions

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 incorporating sustainability considerations
	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 & triple bottom line
		Sustainable design strategies & focus areas to triple bottom line
		Sustainable design strategies & life cycle 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 internal and external 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 of products

3.1. *RQ1 (Receptivity): 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. We use participant quotes to contextualize our observations, demonstrating how our framework was grounded in participant input. This section helps provide a rich picture of the soft side of sustainable design implementation.

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3.1.1. Integrating sustainability into company culture

During our 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 several other participants, including P1 who expressed a desire for Synapse to *"focus on social and ethical considerations"* in addition to environmental ones.

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 project requirements.

Despite Synapse's 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 continued incorporation of the framework in practice.

3.1.2. Relationships with clients and stakeholders

Building on this theme, our interviews further explored where sustainability fits in the client-consultant negotiations, and how client buy-in can prove to 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, as described further in Section 3.1.3. 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 over the course of the PD process.

3.1.3. 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 and engineering considerations. This helped us recognize how professionals can appreciate and adopt sustainable practices for their economic and engineering performance benefits.

 doi:10.20944/preprints202207.0195.v1

3.2. *RQ2 (Tools valued): What do practitioners value in existing sustainable design methods and tools (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 larger repeatable framework to support their selection and application.

3.2.1. 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"* [9]. Synapse employees confirmed that they often used parts of methods as opposed to applying whole methods as prescribed.

Table 2 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 as well as product-level and system-level). 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 2. SDMTs considered and/or selected to be included in the framework

Methods considered	**Env.**	**Soc.**	**Econ.**	**What were these methods valued for?**
Integrated as framework structure:				
Whole System Mapping (WSM)	X	X	X	*"systems-level view"*, *"data-driven"* (supported by insights from LCA)
Simplified Life Cycle Assessment	X			*"quantitative rigor"*
UNEP Design for Sustainability	X	X		*"easy-to-understand categorization of sustainability impact"*
Checklist for Sustainable Product Development	X	X	X	*"comprehensive"*, *"developed in an industry context…might be more relevant than academic tools"*
Strategies selected:				
Okala Ecodesign Strategy Wheel	X			*"selection of strategies by product life cycle stage"*
The LiDS Wheel	X			*"selection of strategies by product 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 quantitative metrics!"*

 doi:10.20944/preprints202207.0195.v1

Factor 10 Engineering Design Principles	X		X	*"Relevant but obvious"*
Product Service System Business Model Landscape	X	X	X	*"Often outside our scope [of influence]"*
Circular Design Guide - Ellen MacArthur Foundation	X	X	X	*"Some useful methods and tools"*
12 Leverage Points	X	X	X	*"Broad, 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 Country Context		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 Fig 4. 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.

3.2.2. 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. 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.

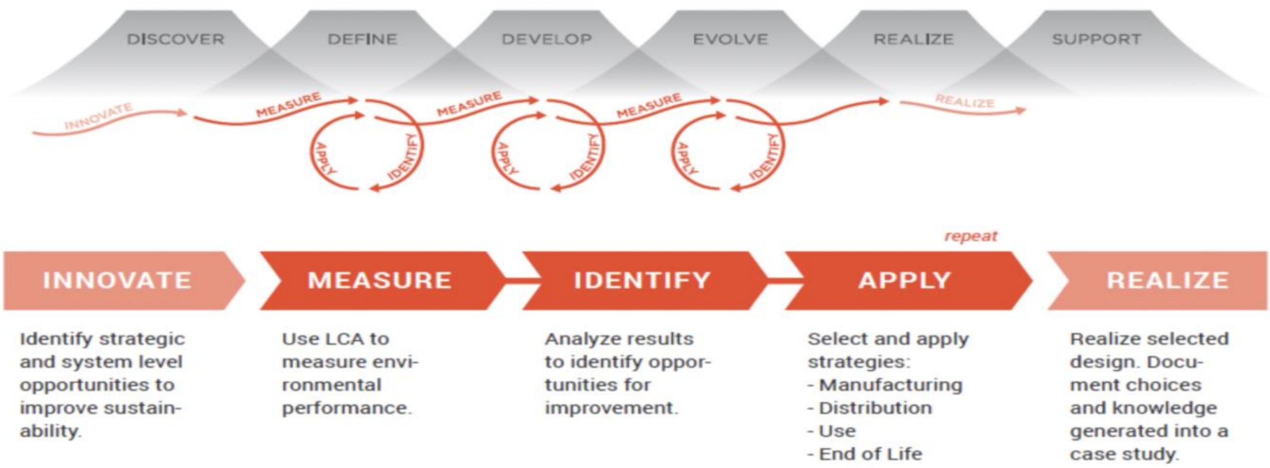

Figure 2. The framework's sustainable design stages (red) are applied iteratively, in parallel to the PD process (gray).

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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."* 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.

3.3. RQ3 (Co-creation): How does co-creating a framework with employees enable long-term integration?

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 fast-paced, iterative PD workflow, as summarized in Fig 3:

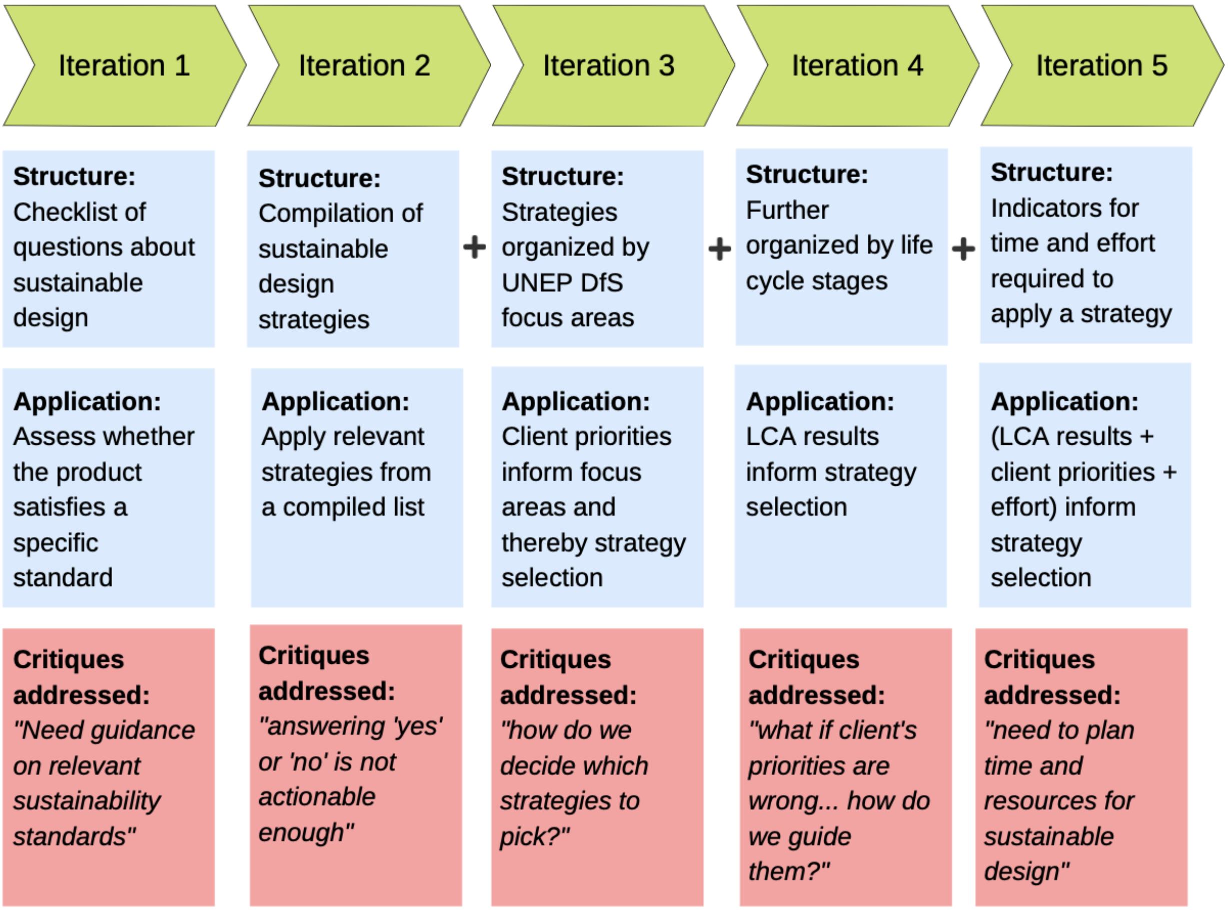

Figure 3. Various iterations in the framework's design

3.3.1 and 3.3.2 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.

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

A critical insight from the participant observation was that users were looking for a structured decision support framework to help with selecting the right strategies. Our co-

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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 [24], 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 [25]. 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 3. Table 5 in the Appendix includes the grouping of strategies by these focus areas.

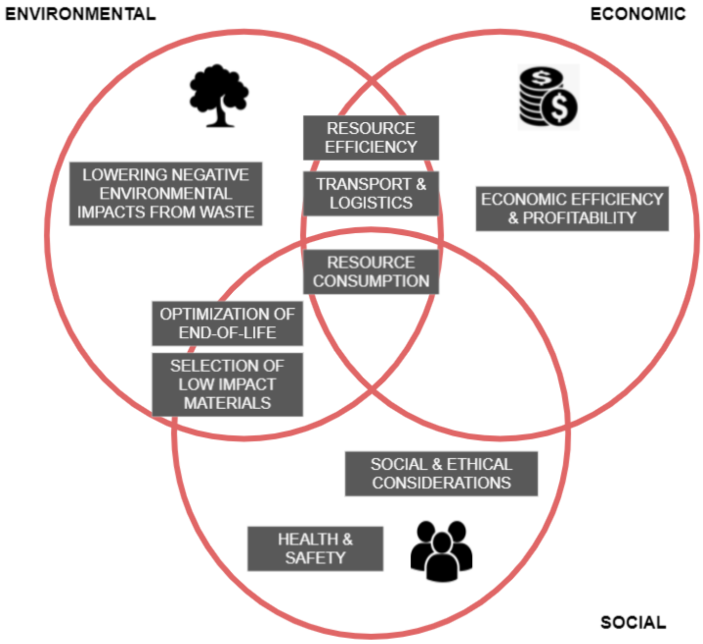

Figure 4. Connecting the sustainability focus areas to the triple bottom line. This helped us address all three pillars of sustainability.

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 3.2.1. 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. Figure 4 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.

Figure 5. Final list of strategies comprising activities/mindsets from existing SDMTs that were found to be relevant and valuable to our participants.

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. The content is expected to grow as more teams learn and apply the strategies.

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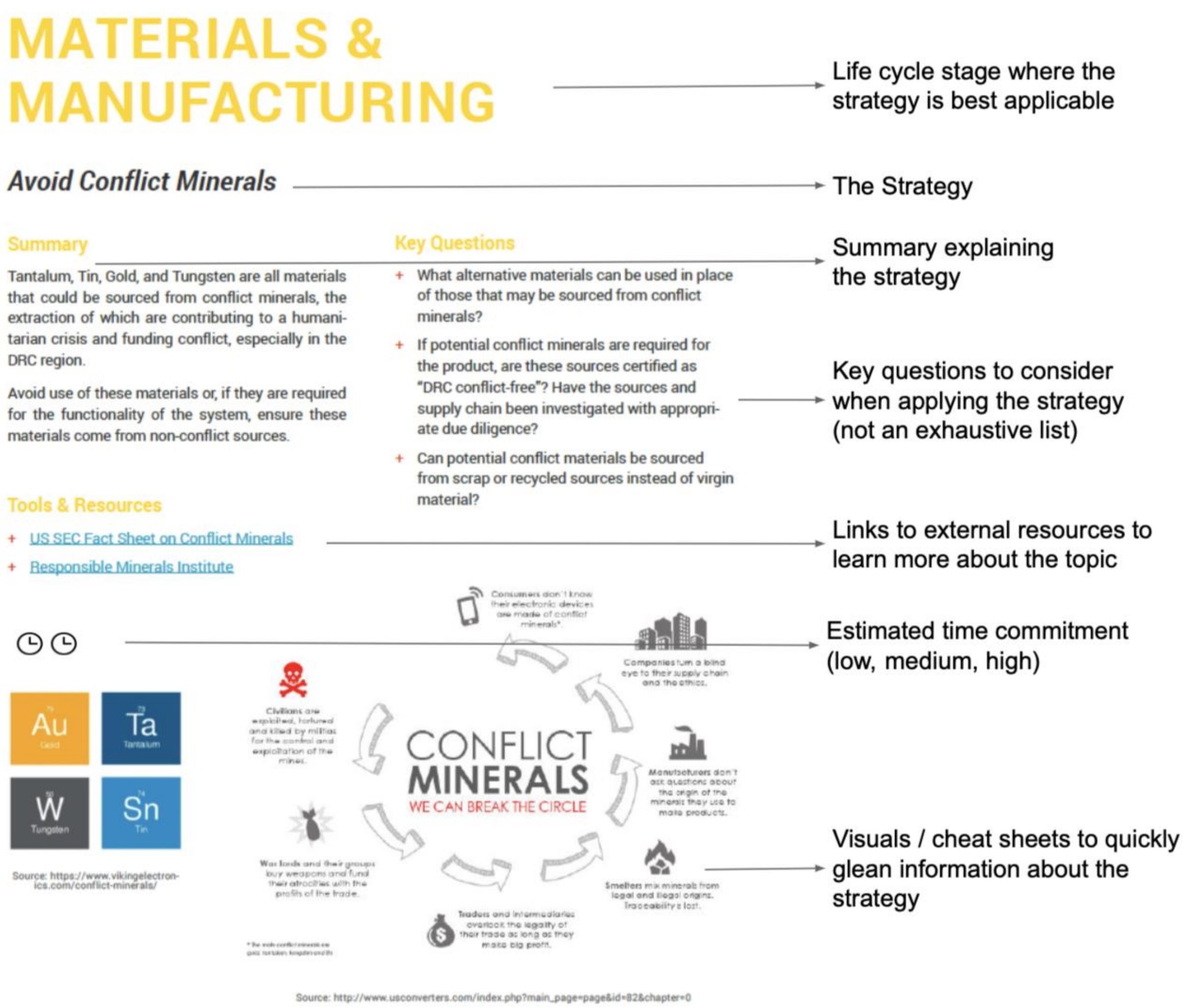

Figure 6. Summary page for each strategy provides key information to support its application

3.3.2. Applying the overall framework in PD practice

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. 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.

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 6 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.

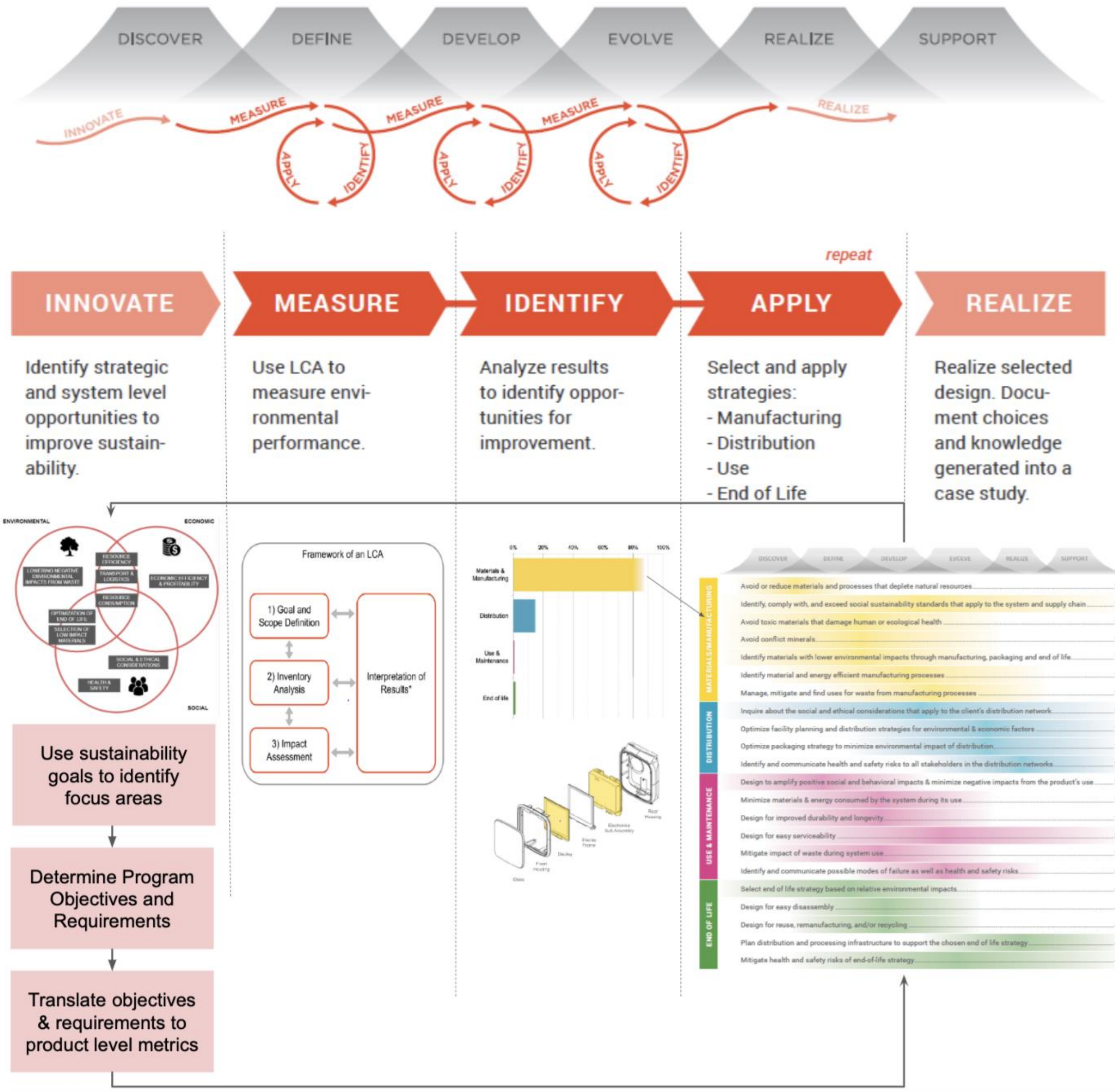

Figure 7. Flowchart detailing the process of applying the sustainable design framework

3.4. RQ3 (Long-term impacts)

We continued to engage closely with Synapse following the conclusion of the first author's 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 [39]. 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 8: a, b, & c) demonstrate the project, sustainable design methods applied, and the resulting improvement in environmental impacts.

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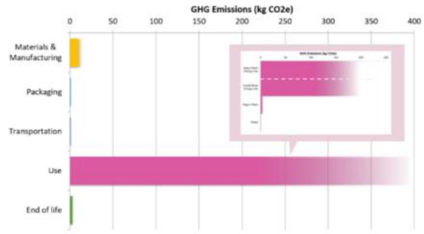
COFFEE MAKER LCA

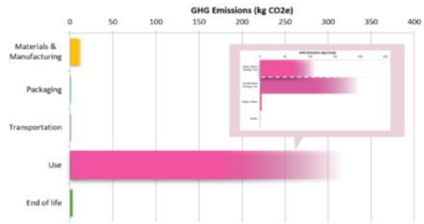
Measured in CO2e, Excluding Coffee

Energy use dominates GHG Emissions

50% of the energy used is in brewing and 50% in keeping it warm



A "Smart" keep warm function reduces total carbon footprint by 20%



MULTIPRONGED APPROACH TO IMPACT REDUCTION

For Consumer Electronics with Mechatronics

- Our design-concurrent LCAs for this product surfaced opportunities in multiple areas, resulting in a **37% reduction of GHGe**

- Reductions include:
  - Transport - reducing use of air freight
  - End of life - achieve 50% recycling rate
  - Charger - use recycled materials
  - Mechanics - mechanical redesign for material efficiency
  - Electronics - reduce IC impact
  - Energy - use renewable energy at the CM

Similar Device

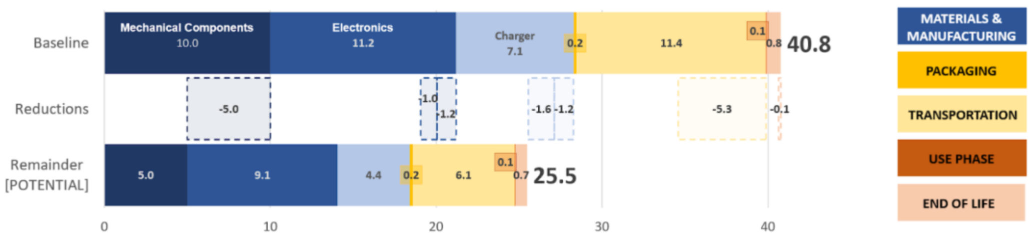


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Figure 8 (a,b,c) Synapse marketing slides from three projects that applied the sustainable design framework - all of which showed a reduction in environmental impacts

Other insights gained from the longitudinal interactions with Synapse are summarized below:

- Personal interest among Synapse employees has been a strong driving force for the integration of sustainable design into their PD process. Leadership support has been 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;

Synapse leadership believes that positive marketing stories resulting in greater client enthusiasm is the external stimulus necessary to make sustainable design a habit. They are encouraged to have had four sustainable-design-focused projects over the past two years and are hopeful that the numbers will rise.

4. Discussion

We 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. We conclude now by synthesizing how these findings address our research questions.

4.1. Synthesizing insights around our research questions

As denoted throughout the Results section, the insights discovered through interviews and discussions helped answer our research questions and informed the sustainable design framework. We synthesize our findings as they relate to each research question in Table 3.

Table 3. Insights organized by research questions

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 to easily select the right strategy for the problem at hand
	Structured approaches to aid application of strategies iteratively
	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 the company's 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

Our 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 our 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. We saw this company-wide inclination towards sustainability align with a growing interest among their clients to develop more sustainable products and services.

Next, we investigated perceived benefits and costs of extant sustainability practices, ***RQ2: What do professionals value in existing SDMTs?*** We 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 just on the environmental aspects, but also on the social and economic aspects of sustainability.

We were 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?*** Facilitated by the first author embedded in the company as an intern, co-creation allowed us 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 our participants' agency, buy-in, and the ultimate efficacy of the solutions produced. Our experience indicates that co-creation helped promote the continued application of the framework in practice following the completion of the study.

Finally, we sought 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, we continued to communicate with the company for a year after the framework was developed, learning how it had been applied on projects and refinements made 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 more sustainable products and services.

4.2. Opportunities for future work

Our case study partner reported on the framework in a white paper, to encourage additional companies to adopt and provide experiences with the approaches. They have so far received positive feedback from companies in other industries, suggesting the generalizability to other PD contexts beyond consumer electronics. We believe that the iterative human-centered approach used to co-create the framework with the employees is a key generalizable takeaway for academics and professionals working in sustainability. The specific shortlist of methods compiled for Synapse may need case-specific tailoring and co-creation in a different company and industry, which helps with receptivity and retention of practices. An important next step is to systematically test the utility of the framework on a broader scale. We are therefore currently conducting a new study at a company in a different industry to better understand the broader application of the framework, including how it would translate from a consulting firm to a product firm. Further, we predominantly applied qualitative methods to deeply engage stakeholders in our Synapse case study, in order to gather a rich, highly contextualized dataset about their experiences and needs. While these participants spanned a variety of disciplines, roles, and levels of seniority, it was a relatively small-scape sample, motivating future work that connects with larger numbers of employees, for instance through surveys to gather more quantitative data and triangulate in on insights through these mixed methods.

5. Conclusion

This paper explored how sustainable design practices can be systematically integrated into the PD process at an engineering consultancy firm. The first part of our study involved the first author being embedded into the firm as an intern, in order to better understand their PD workflow and build trust and rapport with the participants. During this time, she conducted semi-structured interviews and group discussions to gain deeper insight into their processes, and to co-create a modular sustainable design framework that could be flexibly applied to suit the firm's context and needs. The second part of the study involved weekly check-ins for a period of over a year, in order to follow the company's application and adaptation of the framework to serve four actual PD projects. This longitudinal engagement enabled us to evaluate the effectiveness of the framework in supporting the integration of sustainability considerations in practice, including to gather feedback and implications for how to improve the framework going forward.

In summary, the sustainable design framework presented in this paper provides a structure to enable the effective consideration of sustainability throughout PD. Co-created with practitioners, the framework follows an iterative process of measuring impacts via LCA, identifying hotspots, and applying appropriate strategies (activities and mindsets) from a compiled list of SDMTs that we identified as relevant and valuable to the company context. The framework organizes the list of strategies in terms of the most salient PD phases and life cycle stages, thereby offering multiple levers for selection. Basing the selection of strategies on the hotspots identified through simplified LCA adds a data-driven perspective. Flexibility is further supported by allowing users to pick one or more strategies from various SDMTs, as opposed to having to apply a single method as a tunnel process. The strategies are also correlated to various sustainability focus areas to allow users to make choices based on a client's sustainability priorities, additionally creating opportunity for discussion of priorities if such priorities are yet to be identified. Overall, we look forward to the continued dissemination of our contributed framework, co-creation methods, and broader insights to support the translation of sustainable design research into industry practice.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: Conceptualization, Jeremy Faludi and Tejaswini Chatty; methodology, Tejaswini Chatty and Elizabeth L. Murnane.; validation, Elizabeth L. Murnane.; formal analysis, Tejaswini Chatty and Hana H. Ba-Sabaa; investigation, Tejaswini Chatty and Will Harrison.; resources, Will Harrison; data curation, Tejaswini Chatty and Hana H. Ba-Sabaa.; writing—original draft preparation, Tejaswini Chatty, Hana H. Ba-Sabaa, and Elizabeth Murnane; writing—review and editing, Tejaswini Chatty and Elizabeth L. Murnane; visualization, Tejaswini Chatty and Jeremy Faludi; supervision, Jeremy Faludi and Elizabeth L. Murnane; project administration, Will Harrison; funding acquisition, Will Harrison. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Dartmouth College (protocol code STUDY00031944 and 11/22/2019)

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.
Data Availability Statement: Not applicable

Acknowledgments: We would like to thank all the employees of Synapse who worked with us to help integrate sustainable design practices into their product development workflow.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix

Table 4. Characteristics of Synapse employees involved in our case study, including their current role at Synapse as well as educational and employment experiences

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Participant	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 5. 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
	x			Avoid conflict minerals
Selection of low impact materials	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
		x		Inquire about the social and ethical considerations that apply to the client's distribution network
Social and Ethical Considerations	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
	x		x	Design for easy disassembly
Optimization of end-of-life	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	

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