EcoSketch: Promoting Sustainable Design through Iterative Environmental Assessment during Early-Stage Product Development

Article *in* ACM Journal on Computing and Sustainable Societies · February 2024

DOI: 10.1145/3648436

Jeremy Faludi
Delft University of Technology

Elizabeth Murnane
Dartmouth College

EcoSketch: promoting sustainable design through iterative environmental assessment during early-stage product development

TEJASWINI CHATTY, Dartmouth College, Hanover, United States
BRYTON L. MOELLER, EarthShift Global, Hanover, United States
IOANA A. PANTELIMON, Dartmouth College, Hanover, United States
CATHERINE D. PARNELL, Dartmouth College, Hanover, United States
TAHSIN M. KHAN, Dartmouth College, Hanover, United States
LISE LAURIN, EarthShift Global, Hanover, United States
JEREMY FALUDI, TU Delft, Delft, The Netherlands
ELIZABETH L. MURNANE, Dartmouth College, Hanover, United States

Sustainability has long been a topic of substantial interest the design and human-centered computing communities. With industries increasingly prioritizing climate targets, there is a growing demand for sustainable product design. This paper addresses this need through EcoSketch, a digital tool designed to democratize environmental impact assessments for product designers. Shifting typically retrospective evaluations to the early stages of product development, EcoSketch enables proactive consideration and adoption of sustainable alternatives. Unlike software tailored to environmental scientists, it minimizes the need for specialized training or extensive data inputs. We delve into the development and evaluation of EcoSketch, highlighting its unique features and usability strengths. The paper concludes by discussing design implications and proposing future research avenues to strengthen the intersection of human-computer interaction and sustainable product design, advancing progress on environmental challenges at the systems level.

CCS Concepts: • **Social and professional topics → Sustainability**; • **Human-centered computing → Human computer interaction (HCI)**.

Additional Key Words and Phrases: Environmental Sustainability, Sustainable Design, Product Design, Life Cycle Assessment

1 INTRODUCTION

Public, private, and academic discourse continues to grow around issues of sustainability and ways to mitigate climate change. As frequent extreme climate events threaten our energy systems [38], food systems [24], and biodiversity [23], industries including those engaged in product development (PD) are setting ambitious targets around the sustainability of their operations. These high-level targets, for e.g., achieving carbon neutrality, trickle down into everyday PD practice in the form of decisions related to a product's materials, manufacturing processes

Authors' addresses: Tejaswini Chatty, Dartmouth College, Hanover, United States, tejaswini.chatty.th@dartmouth.edu; Bryton L. Moeller, EarthShift Global, Hanover, United States, bryton@earthshiftglobal.com; Ioana A. Pantelimon, Dartmouth College, Hanover, United States, ioana.andrada.pantelimon.th@dartmouth.edu; Catherine D. Parnell, Dartmouth College, Hanover, United States, catherine.d.parnell.22@dartmouth.edu; Tahsin M. Khan, Dartmouth College, Hanover, United States, tahsin.m.khan.th@dartmouth.edu; Lise Laurin, EarthShift Global, Hanover, United States, lise@earthshiftglobal.com; Jeremy Faludi, TU Delft, Delft, The Netherlands, j.j.faludi@tudelft.nl; Elizabeth L. Murnane, Dartmouth College, Hanover, United States, elizabeth.l.murnane@dartmouth.edu.

ACM 2834-5533/2024/2-ART
https://doi.org/10.1145/3648436

and facilities, energy efficiency, circular end-of-life models, and other sustainable design strategies that can help to reduce environmental impacts.

To quantify those impacts and select specific strategies, a modeling technique called life cycle assessment (LCA) is typically utilized to assess hotspots of environmental impact (e.g., global warming, ozone layer depletion, human health effects, etc.) across all of the product's life cycle stages from material extraction through manufacturing, transportation, usage, and eventual disposal. More specifically, performing an LCA involves four main steps: goal and scope definition, life cycle inventory, impact assessment, and interpretation of results.

LCA is the single most common approach for sustainable product development [1] and [16]. However, several shortcomings hinder the usability and effectiveness of current LCA software. In particular, studies find that existing industry-standard LCA tools (e.g., GaBi and SimaPro) are (1) highly challenging and time-consuming to learn and use, which impedes their accessibility for novice users and LCA non-experts, and (2) require extensive and exact data about product details to make calculations, which makes them inapplicable during early portions of the product design process when such information is still being explored and iteratively finalized [10]. Our research focuses on addressing these key challenges.

The life cycle inventory step generally takes the most time, as the analyst conducts research to precisely identify and quantify all the input and output energy and material flows in the system, often collecting data from a variety of stakeholders, while ensuring that it meets quality standards required for reporting, regulatory compliance, and marketing purposes. This contributes to LCAs generally being performed by *expert* analysts at the *end* of a product development cycle, when this granular data (e.g., on masses of parts, manufacturing processes, production locations) is available [49]. Further, designers and engineers developing products report that LCAs are too time-consuming overall and are performed too late in the design cycle to lead to any viable design changes [18]. Overall, most existing tools therefore cater to retrospective analyses after product development is finished, and LCA remains underutilized at the early PD stages where it can make the biggest difference [10].

Indeed, there is growing consensus on the need to assess possible environmental impacts during *early* stages of product development, to inform subsequent design decisions that can significantly influence the sustainability of a product over the course of its life. But supporting early-stage LCA is non-trivial given a contradiction referred to as the "ecodesign paradox", which reflects the fact that preliminary product development phases offer the greatest opportunity for improvement at the lowest cost, as this is a highly flexible period when design decisions are still fluid; yet that lack of product knowledge makes it challenging to actually calculate accurate assessments, particularly using standard LCA tools that are not equipped to handle uncertain inputs.

"Simplified LCA" tools (e.g., Sustainable Minds and Ecolizer) are positioned as having been designed for the product design context, but do not meet critical usability needs of the target audience such as: (1) accounting for the uncertainties in input data inherent in early-stage PD, (2) being efficient to use within tight project timelines, and (3) being intuitive to learn [10]. They also suffer from outdated life cycle inventory databases making their results less credible for users aiming to perform lightweight yet robust environmental assessments. A variety of other sustainability tools come and go, including calculators and widgets for less-technical audiences, such as the Microsoft Sustainability Calculator [48], the Idemat app [33], the Sustainable Apparel Coalition's Higg Product Module [42], the BEAM Estimator [26] currently in Beta, and the CARE tool [31] in development. Such growth is a testament to the need for digital tools that can support sustainable design practices.

In this paper, we present a lightweight LCA tool that is tailored to non-experts and addresses the challenges of the ecodesign paradox by enabling reliable environmental assessments during early stages of product development. Figure 1 illustrates a user journey through such a process of applying LCA early-on in PD to inform design and engineering decisions. In addition to assessing and comparing the impact of various design choices (e.g., about material choices, manufacturing locations, supplier selection, energy use, and end-of-life treatment including recycling or landfill disposal), 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

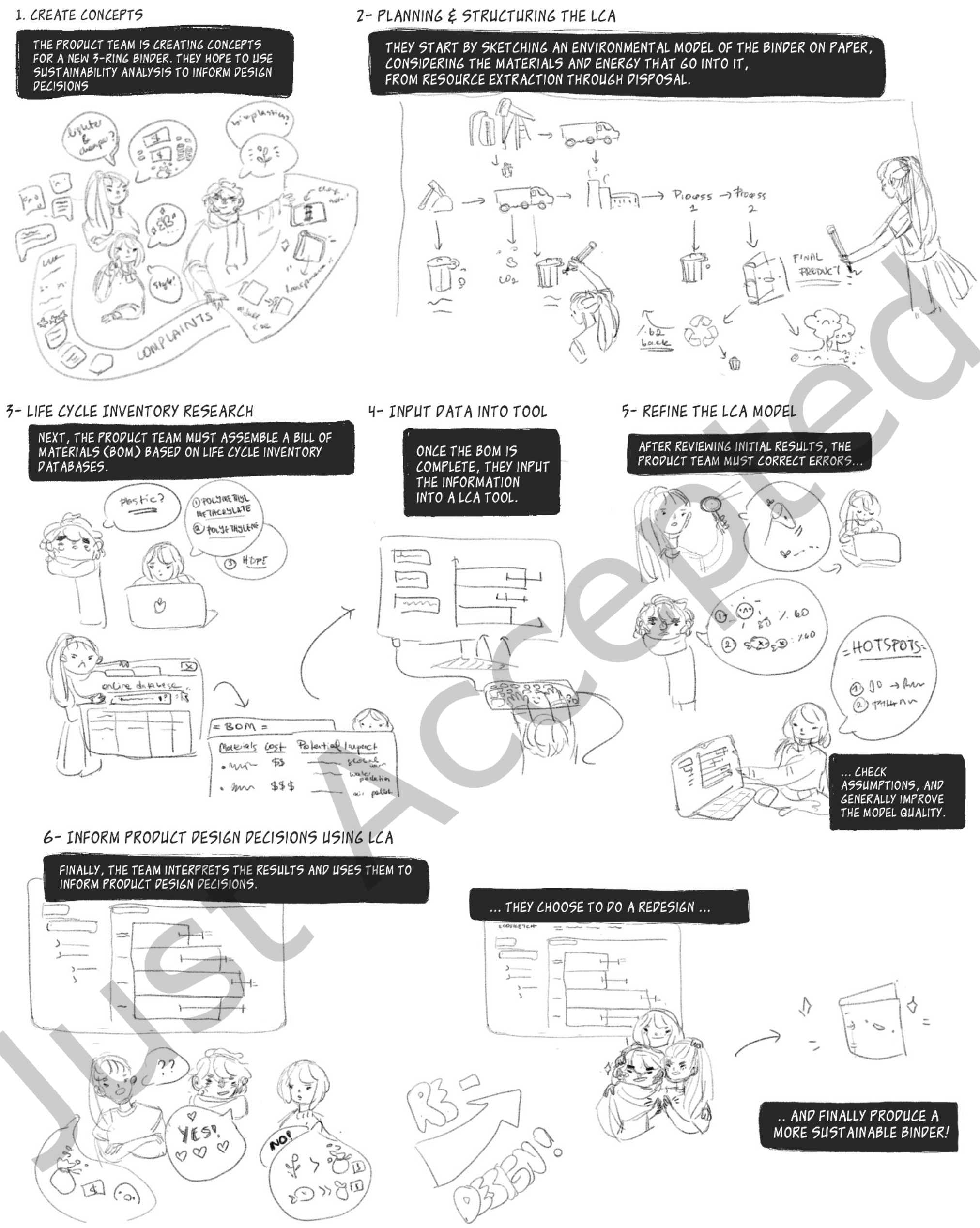

Fig. 1. Storyboard detailing the process of performing an LCA during product development

potential to support data-driven and science-based decision-making, meaningful sustainability improvements, lesser greenwashing, and greater accountability in product design. They also help illuminate how day-to-day PD choices add up towards higher level sustainability targets such as achieving carbon negativity by 2050.

Our work to develop this tool was guided by the following research questions:

(1) How might we design LCA software that is **easy to learn and use** and **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 design 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 sustainable design tools for the future?

2 RELATED WORK

Sustainable Human-Computer Interaction (SHCI) refers to research focused on limiting the environmental impacts of technology or on using HCI as a means to promote environmentally friendly outcomes. Since early publications that introduced a sustainability perspective to interface design, SHCI has increasingly grown in priority among HCI researchers. Much of the emphasis has been on eco-feedback technology that targets personal behavior change, for example by providing people with feedback on their electricity or water use in order to persuade less consumption [13]). However, critiques of the SHCI literature have identified the importance of expanding this scope beyond the *individual*, especially considering the scale of reduction achievable by individual behavior change may be limited to less than 10% [25]. In contrast, the Carbon Majors report 2017 identified that just 100 companies historically are responsible for 71% of global emissions [22], which points to the importance of recalibrating SHCI research towards *industry*, including to develop digital tools that improve industrial sustainability practices. In this paper, we therefore focus on bridging SHCI with *industrial level systems change* by enabling the use of life cycle assessment techniques in early-stage product development.

In the following subsections, we aim to build bridges between the sustainable HCI and sustainable product design communities by first elaborating on trends in sustainability-related HCI research, then examining the lack of published research in HCI venues on sustainability tools designed for industry users, and finally summarizing publications related to digital tools that have appeared in the sustainable design and engineering design literature.

2.1 Trends in sustainability-related research in human-centered computing venues

It has been 15 years since the first SHCI publication on "sustainable interaction design" (SID) [4]. In that foundational article by Eli Blevis, a rubric is provided to promote SID by offering considerations such as recycling, remanufacturing, repair, reuse, salvage, longevity of use, and more, while further highlighting that software and hardware are intimately connected in a cycle of mutual obsolescence with big implications for the environment.

We reviewed literature published at HCI venues since that article originally appeared (i.e., since 2007) using keyword searches in the ACM digital library including *environmental sustainability*, *sustainability, environmental impact*, and *digital sustainability* in the title and full article. Our review showed that papers published in the SHCI space broadly fall into the following categories: personal eco-feedback technology, development of efficient software, design theory and frameworks, digital tools for sustainable design, and literature reviews and critiques. Our characterization aligns with the topics identified in a recent review paper [7].

Papers in the space of 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 [20]. This work often intersects HCI with the field of environmental psychology. As examples, [35] looked at the receptivity of personas with diverse age ranges to eco-feedback formats such as electricity bills. Other work [28, 39] designs applications that inform users about their electricity consumption or incorporates gamification to enhance persuasion. Research has also studied how technology can leverage social or peer influence to promote sustainable behaviors [35].

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 [52], technical infrastructure [39], and digital services [40]. Design frameworks have also been offered to help technologists consider strategies for reducing the energy and space consumption requirements of digital devices [12]. This emerging field of sustainable software engineering is important and exciting; however, it does not address the development of *tools* to help analyze environmental impacts and support sustainable design practices.

In fact, there has only been one published paper at these conferences focusing on the development of a digital artifact or system for the sustainability needs of industry design practitioners. That tool, Sourcemap [5], aimed to quantify the carbon emissions from complex global supply chains, and was developed through a year-long participatory design research process with five small businesses. Reviews of the SHCI literature acknowledge that it is extremely complicated to develop tools like Sourcemap in the life cycle analysis space for industry applications [7], which helps to explain why such work is rare so far. We hope our work helps the HCI community take a meaningful step in that direction.

Another main area of SHCI research focuses on critique. A recent review of the landscape [7] included 35 articles published since 2009, with an emphasis on identifying what has been missing in SHCI literature to date. That paper asks, "what are they asking HCI researchers to do for sustainability?" Critical pieces over the years have recommended that HCI researchers focus on (1) collaboration with experts across disciplines in sustainability such as climate science, ecology, and life cycle analysis [45]; (2) setting shared sustainability goals for the HCI community [29]; (3) devising solutions to structural problems outside the realm of technology development [14]; (4) supporting activism [21]; and (5) addressing problems with the free market economy [41]. Bremer et al. [7] conclude by proposing that to promote broad change, we should target "green policy informatics", which refers to the use of data and informatics to promote sustainable development initiatives. In response to this charge, we work to tackle the massive environmental impacts that result at the level of industrial production, by developing SHCI solutions that respond to the need for informatics tools tailored to this sector.

2.2 Research on digital sustainability tools from outside HCI

To reiterate, the HCI community has engaged with promoting sustainability at the *individual-level* and at the *policy-level*. We emphasize the need for attention on another layer of human activity: industry-scale product development practices. Research on digital life cycle analysis tools for industry applications do exist. For instance, recent work has looked at shortcomings in existing professional LCA tools in catering to product development needs [10] and how such tools might be better integrate into other aspects of the PD workflow (e.g., computer-aided design activities) [46]. Research has also studied the design of digital life cycle analysis tools for specialized industrial applications such as furniture design [3], green chemical engineering, building design and architecture [32], and biofuels [37].

However, this work has been exclusively published in journals and conferences outside the HCI community, further contributing to the general lack of cross-pollination between HCI and sustainable product development. This disconnect cuts both ways: the SHCI community is missing out on an imperative opportunity to advance industry-level sustainable development practices, and this lack of attention has led to a stock of existing tools that have not been designed through user-centered approaches to make them approachable and effective for users without specialized training. There is therefore a mutual need between the HCI and product development communities, to create interactive tools that enable better sustainability sense-making and decision-making and, in turn, help promote systems-wide industrial change.

3 ECOSKETCH: A LIGHTWEIGHT ENVIRONMENTAL ASSESSMENT TOOL TO SUPPORT SUSTAINABLE DESIGN DECISION-MAKING DURING EARLY-STAGE PRODUCT DEVELOPMENT

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). The following sections describe the main features of EcoSketch, including how its design process was directly informed through close collaboration with real industry PD practitioners.

3.1 Industry-engaged design process

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 for EcoSketch, we conducted four months of field work at Synapse Product Development (Synapse), a product development consultancy, with the overall objective of understanding how life cycle assessment and other sustainable design methods can be better integrated into industry practice. Results from the user research are published in [10] and summarized in this section.

Synapse is a boutique engineering consulting firm with approximately 100 engineers who engage in hardware product development projects in the consumer electronics space. Four employees participated in the study by learning to use five different existing LCA tools ranging in complexity. SimaPro and GaBi are industry-standard tools designed for use by LCA experts performing ISO-certified analyses, while Sustainable Minds, Ecolizer, and EarthSmart are light-weight LCA tools. All participants learnt to use all tools, and shared qualitative feedback through interviews and think-aloud tests as well as semi-quantitative feedback through a survey. Survey results showed that lightweight LCA tools were preferred over the complex options for quick use in the fast-paced PD context. Thematic analysis of the qualitative data and brainstorming with the participants yielded the following how-might-we (HMW) design prompt questions to guide the development of future LCA tools including:

(1) HMW manage the ways time constrains the application of LCA in early-stage PD?
(2) HMW make LCA results more reliable by accounting for the various inherent uncertainties?
(3) HMW facilitate iterative refinement of LCA models as well as speedy error recovery?
(4) HMW support the interpretation and communication of results?

Design recommendations addressing these prompts were generated in collaboration with participants, listed in [10], of which 24 recommendations were eventually implemented in EcoSketch. Participants from this user study remained in regular contact with our design team and provided ongoing feedback throughout the iterative prototyping of interfaces and features.

Once we reached the stage of functional implementation, we further sought the input of LCA professionals at EarthShift Global (EarthShift). EarthShift has a staff of experienced LCA professionals who conduct LCAs, provide LCA coaching services, and develop heavyweight LCA software. They have been closely 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 appropriate analytic outputs to users. Notably, we have forged a relationship with EarthShift 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. Overall, the genuine partnership between our team of

HCI researchers, PD practitioners, and sustainability experts is evidenced by the presence of these collaborators in the paper's authorship.

3.2 System components

Translating our 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 2 illustrates how EcoSketch's components interact with each other to enable users to perform simplified LCAs during product development.

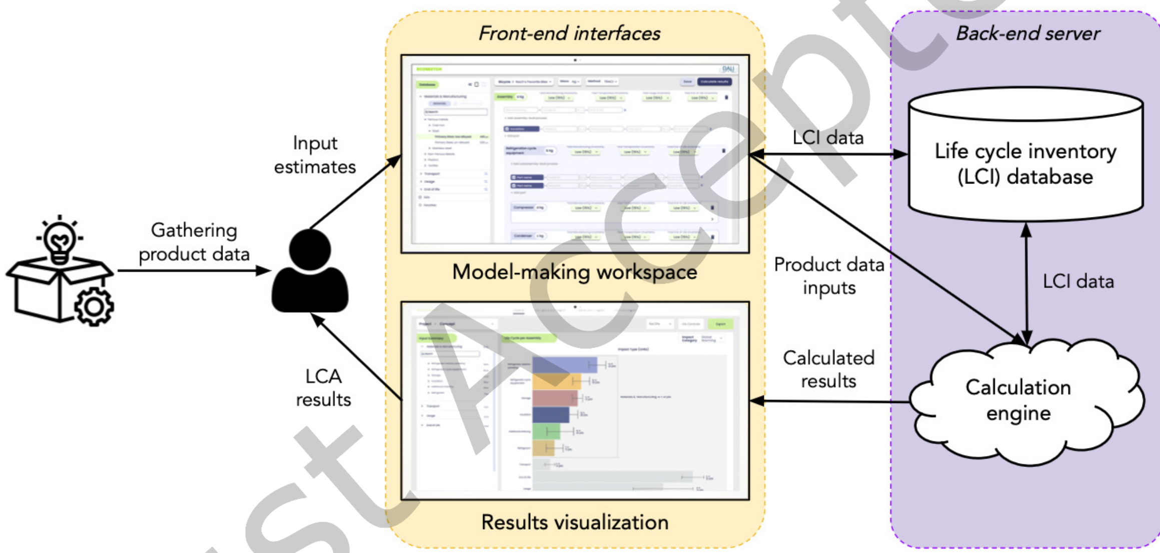

Fig. 2. The high-level system architecture of EcoSketch

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

3.2.1 Model-making canvas. In order to perform an LCA, users 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 product development. 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. For example, in the case of the 3-ring binder described in the storyboard in Figure 1, the outer casing could be listed as a sub-assembly with two parts, a cardboard interior and a plastic exterior. The weights of these parts would be estimated in kg.

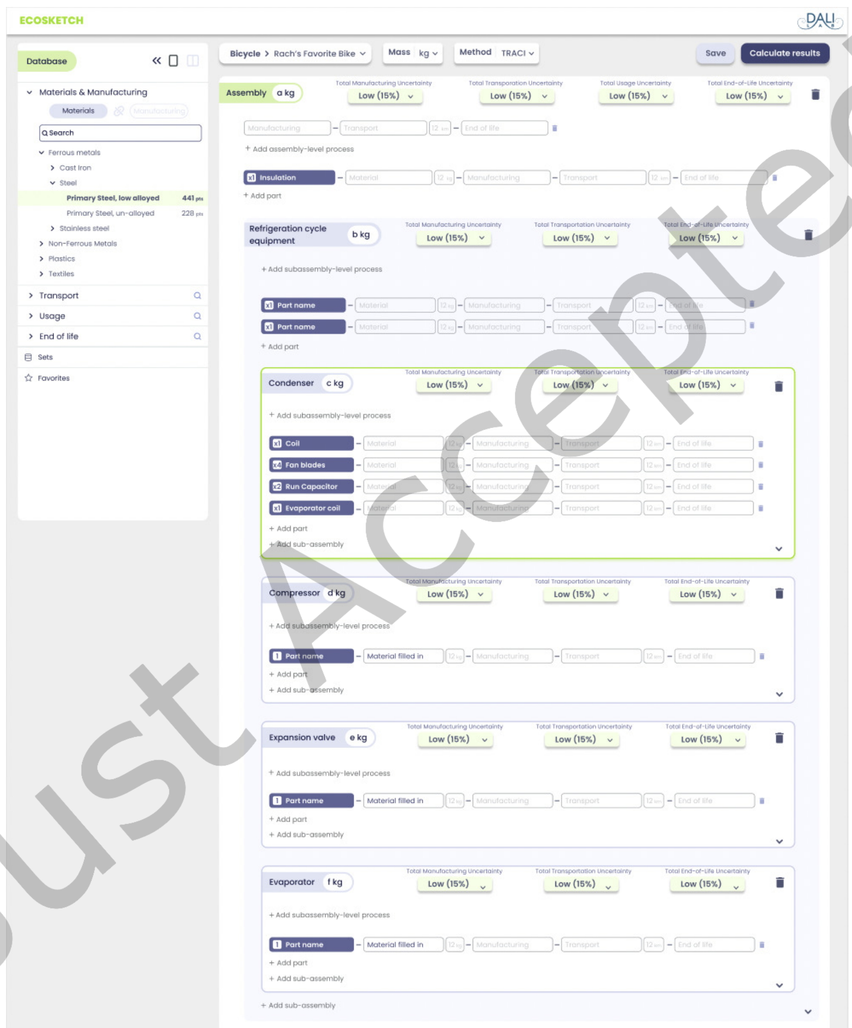

Fig. 3. EcoSketch's model-making canvas

Users spend a majority of their time during the LCA process building their model. It is therefore vital for lightweight LCA tools like EcoSketch to make the model-making process as intuitive and easy as possible. To improve the ease of model-making, we incorporated the following design decisions, which were further 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, which is different from the flows, parameters, and processes that traditional heavyweight LCA tools use and that our preliminary research indicated are often confusing for practitioners to adapt to. This product structure decomposition aligns with theories of mechanical design engineering that practitioners are familiar with [44].
- *Matching mental models to product models by organizing via 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 users because the bill-of-materials 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 utilized by practitioners (e.g., using "ABS" instead of "acrylonitrile-butadiene-styrene copolymer"). To remain universally flexible, however, EcoSketch's search function supports both the specialized LCI terms and colloquial PD terms. Further, EcoSketch incorporates not only structures but also terminology from CAD software to additionally ease the tool's learning curve.
- *Linking PD processes to product materials:* EcoSketch links relevant manufacturing processes to each material, which simplifies the process of searching and sorting through the massive LCI database to build an LCA model. For example, if a part is made of ABS, the tool recommends salient manufacturing processes such as injection molding.

3.2.2 Under-specification. Prior work by [36] 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 a practitioner is modeling the 3-ring binder we have been using as an example, 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 under-specification, 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 displayed results. Error bars were chosen to visualize uncertainty based on preferences gathered from similar practitioners in recently related work [47]. Still, we call out that there are rich opportunities for further research to explore and rigorously test other novel uncertainty visualizations for the early-stage PD context.

- *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 the results. If a part within the set is identified as a significant contributor to overall impacts, the user 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 user 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.

3.2.3 Database. The database portion of an LCA tool includes life cycle inventory databases (e.g., from sources such as ecoinvent [19, 50]), that compile the environmental impact factors for a variety of materials and processes. For EcoSketch, we use data from ecoinvent3, which is compiled by a not-for-profit association 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 4.

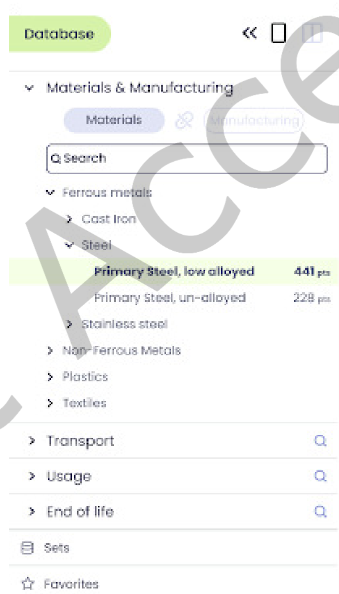

Fig. 4. EcoSketch's back-end includes a database based on ecoinvent3, which compiles the environmental impact factors for various product materials and PD processes.

3.2.4 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 5 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, EcoSketches uses error bars. Several other visual forms were considered including blurs, triangles, and box-and-whiskers; but we settled on error bars given prior research that finds practitioners perceive them as the easiest to understand when interpreting LCA results [47].
- *One impact category at a time:* Earlier versions of EcoSketch included a graph that showed the environmental impacts across 18 different impact categories (e.g., global warming, freshwater eutrophication, terrestrial ecotoxicity, troposphere ozone, etc.) relative to each other on a percentage scale. However, testers found this graph confusing and difficult to interpret. Based on this feedback, we designed all graphs in the visualization page to focus on one impact category at a time instead of multiple.
- *Highlighting overlapping error bars:* The bar graphs highlight any overlapping error bars across bars in a chart. This alerts the user that they cannot make a conclusive decision when comparing the bars, and probably need to specify their inputs further to reduce uncertainty in the model.

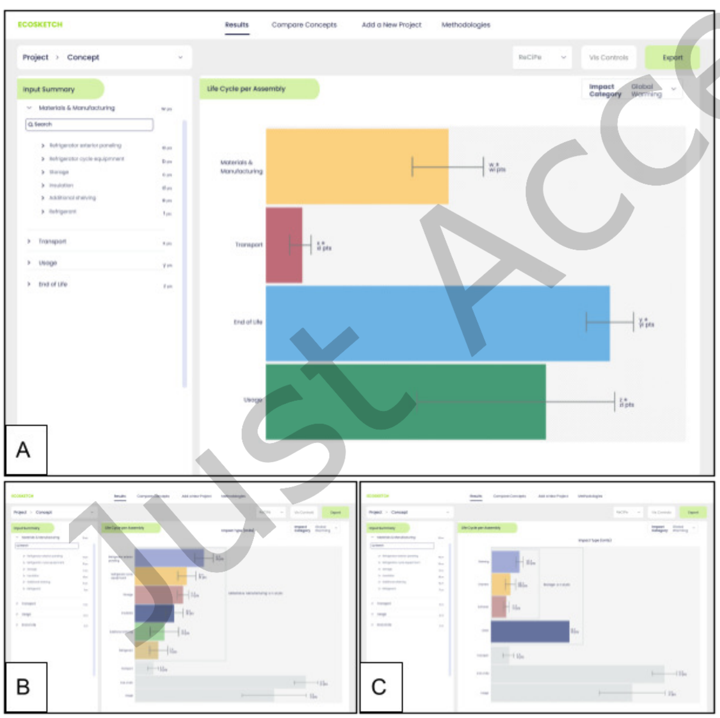

Fig. 5. Graph A displays environmental impacts by life cycle stages. Clicking on one of the bars lets users dig down to the sub-assembly and part-level impacts.

3.2.5 Employing HCI principles to generally enhance user experience. This subsection overviews various features and design decisions that we made based on established usability heuristics [34], to generally enhance the user experience throughout EcoSketch.

(1) **Flexibility and Efficiency of Use**
  - *Better nesting and alignment:* Collapsible sub-assemblies allow users to scroll through a complex model with ease.
  - *Reorganization:* Parts and sub-assemblies can be moved by dragging and dropping them to reorganize model structure and hierarchy.
  - *Save favorites:* The tool allows users to save frequently used materials and processes to a favorites folder for easy access.

(2) **Recognition over recall**
  - *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'm inputting data for". EcoSketch therefore presents the database adjacent to the model so that users can directly see and manipulate the model by dragging inputs from the database.
  - *See the full picture:* Instead of using different tabs or screens for different LCA stages as most tools do, EcoSketch displays the entire model in a one-stop-shop screen to simplify the modeling workflow.

(3) **Aesthetic and minimalistic design**
  - *Search bar color and position:* Our user testing with a high fidelity prototype showed that people struggled to find the search function where it was located, with a dark background. Most users did not notice the search bar and manually looked through the database instead. We therefore divided the EcoSketch database into inputs for each of the life cycle stages, with each section having its own higher-contrast search bar that is more noticeable, as seen in Figure 4.
  - *Dig deeper in the same graph:* Instead of looking at multiple graphs, users can visualize impacts from lower levels of the hierarchy in the same graph. Specifically, a sub-assembly bar dynamically breaks down into its constituent parts when clicked, as shown in Figure 5

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.

4 SYSTEM EVALUATION

Our evaluation of EcoSketch focused on answering the research questions outlined at the end of the Introduction, 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.

4.1 Participants and study conditions

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. To ensure participants had expertise at least on par with an entry-level PD practitioner, we screened based on product design experience. All undergraduate participants took at least two engineering product design classes. Many took more additional advanced product design classes and interned at companies. All the graduate student participants took at least two engineering product deign classes, and had experience designing and developing hardware as part of their research and/or industry positions. Further, we individually verified that each participant was representative of the industry professionals we had interacted with throughout our formative and iterative design phases, based on the similarities we observed in their tool usage behaviors and qualitative feedback. The Dartmouth College Institutional Review Board reviewed and approved all procedures.

To begin the study, participants were consented, including to grant permission to record voices as part of the research team's 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 in the past?

4.2 Research Question 1: Usability of EcoSketch in the hands of novice users

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 performing an LCA on the tool.

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's interface during a think-aloud study. The think-aloud protocol, tutorial, and BOM are included in the supplementary materials.

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 [30]. 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 interview questions:

- On a scale of 1-10, how easy do you think this tool is for novice users to learn? Why?
- Which aspects of the tool did you find the most useful? Why?
- What aspects did you *not* find useful? Why?
- Which aspects of the tool did you find the most intuitive? Why?
- Which aspects 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) [8] was completed by all participants except one (who began but never submitted it) in order to measure subjective perceptions regarding the tool's effectiveness, efficiency, and satisfaction.

4.3 Research Question 2: Workflow efficiency of early-stage product design LCA

Next we examined our second research question, which tests whether EcoSketch does in fact enhance the workflow efficiency of using LCA in early-stage product development, particularly due to its under-specification features (i.e., uncertainty and sets, described in Section 3.2.2). 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 [10]. 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 6 shows screenshots of Ecolizer's workflow. From here on, Ecolizer is referred to in this paper as the "control tool".

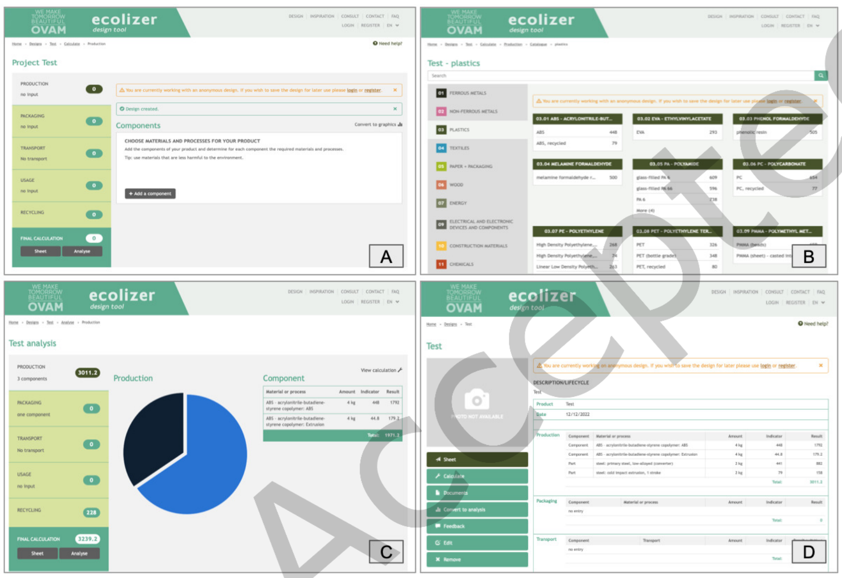

Fig. 6. Screenshots from the control-tool depicting A: model-making, B:LCI data input, C: results visualization, and D: report-making

The interaction flow charts in Figure 7 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. EcoSketch accounts for these uncertainties to calculate estimates of environmental impacts from each part, sub-assembly, and life cycle stage. These estimates help guide users 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.

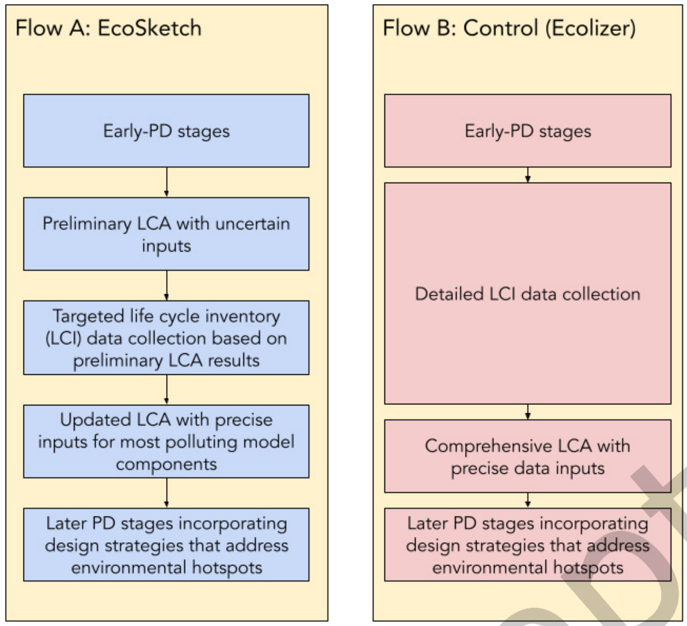

Fig. 7. Interaction Flow A illustrates the EcoSketch LCA workflow, which integrates uncertainty and sets features to support under-specification. Interaction Flow B shows the traditional LCA workflow used by existing tools like Ecolizer

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. 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.

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, we generally 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 us ensure that participants utilized those features appropriately and as expected.

4.4 Data analysis

4.4.1 Thematic analysis of qualitative data. Recordings from the think-aloud test were transcribed and thematically analyzed by the authors [6]. Specifically, two coders reviewed the transcripts and generated initial qualitative codes, which were iteratively refined and combined into higher-level themes. Disagreements were discussed and resolved to ensure inter-coder reliability.

4.4.2 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.

5 RESULTS

Here we report on insights from our user study, which was designed to answer our 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. We organize the following subsections around these questions.

5.1 Research Question 1: Factors contributing to usability for novice users of LCA

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.

Here we elaborate on how we observed that specific EcoSketch features and design strategies contributed to these aspects of the LCA experience. Table 1 then connects these themes to the practitioner needs we had originally identified (see Section 3.1 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 direct and agile manipulation of information during environmental analysis, in large part thanks 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 (about both EcoSketch as a new tool and LCA as a new workflow) was supported by incorporating familiar structures and terminology from product development (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):** We saw that a major benefit of EcoSketch is the way it allowing 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 convey the underlying uncertainty of the model were instrumental in keeping LCA lightweight during not only data input but also sensemaking, while further keeping the workflow accessible to a broad product developer audience.
(5) **Error handling (E):** Finally, we observed the value of including features to prevent common errors (e.g. unit errors) and to facilitate quick recovery from errors that are made.

Table 1. This table connects user needs with relevant design decisions, representative user feedback, and themes extracted from our qualitative data analysis. EP: EcoSketch Participant, CP: Control Tool Participant

Target need	**Features contributing to need satisfaction**	**Representative user reactions (positive)**	**Representative user reactions (negative)**	**Relevant themes about design strategies**
Improve ease of model-building	Use of CAD hierarchy	"I think the use of CAD trees works pretty well for me… I like it" - EP2	"I would like it if you could move this strap [a part] underneath another sub-assembly or make it a separate part" - EP5	**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" - EP1	"It would be nice to copy and paste a part you created in one sub-assembly into another" -EP8	**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" - EP2	"Confusing that materials and manufacturing are next to each other, but the rest of the lifecycle stages have separate tabs at the bottom" - EP6	**F**

Table 1 continued from previous page

	Eliminating unfamiliar terminology	"I didn't know ABS stands for acrylonitrile butadiene styrene! How do you pronounce it?" - EP1	"ABS could also mean 'anti-lock braking system'. Are there acronyms of materials that could mean multiple things? It'd be useful if the full name popped up when I hover" - EP9	**F, L**
Allow users to input uncertain data	Uncertain quantitative inputs	"I like being able to make general estimations using Google for a quick analysis" - EP10	"The dropdown with levels feels simplistic. Would be useful to see the numeric range that a level translates to" - EP8	**F, U**
	Material and process selection by sets	"It's useful to choose a group of hard plastics instead of picking one right now" - EP11	"What on earth is a valid set? Can I put anything in it?", "Does the tool automatically calculate uncertainty when I use a set?" - EP18	**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… [they] are easy to understand" - EP16	"When I hover over the error bar, I want to see the range of numbers" - EP8	**F, U, L, R**

Table 1 continued from previous page

	Highlighting overlapping error bars	"Nice to have guidance on how to interpret the error bars" - EP4	"Too many parts are highlighted and it's distracting" - EP13	**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" - EP12	"[the graph displaying multiple impact categories] is confusing and the least useful" - EP9	**F, U**
Allow faster error recovery and version control	Calculating total mass for each sub-assembly	"I like to deal with errors right away. [This feature] makes sure I don't forget a part" - EP7	"Not clear what this number is doing..." - EP10	**F, E, L**

5.1.1 System Usability Scale (SUS). Results from the SUS survey help inform how usable the EcoSketch system is and where the opportunities for improvement can be found. Figure 8 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 scored)
- 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 scored)
- 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 scored)
- 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 scored)
- 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 scored)

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

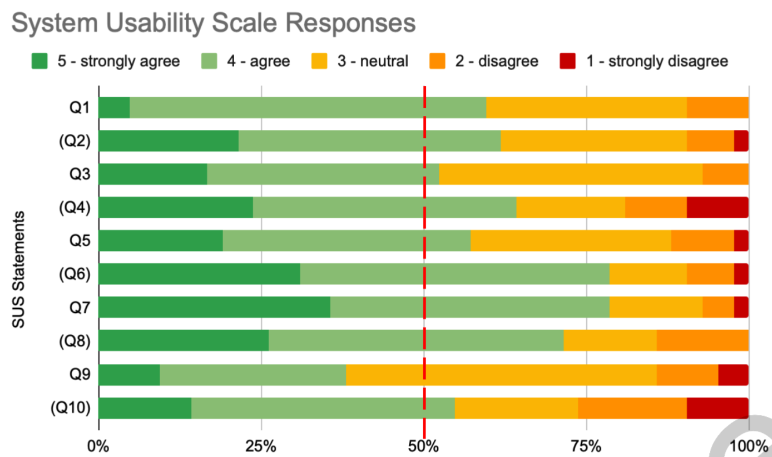

Fig. 8. Stacked bar chart displaying the results from the SUS survey, with reverse-coded questions visually flipped for ease-of-review

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.

5.2 Research Question 2: Efficiency gains from EcoSketch's under-specification approach

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 9 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 10 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.

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 11, 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.

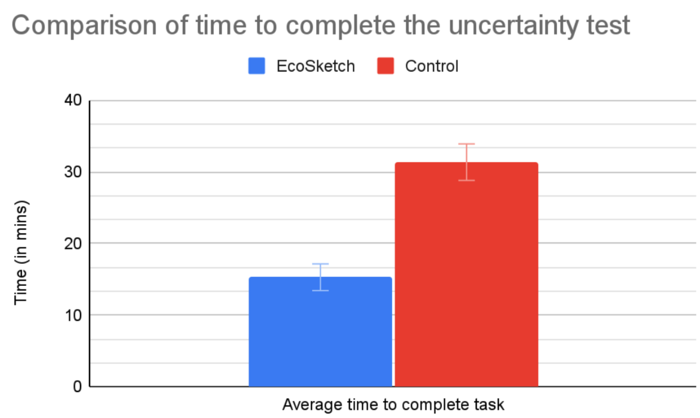

Fig. 9. Average time taken to complete a model using EcoSketch (left) vs. a popular existing LCA tool as a control (right)

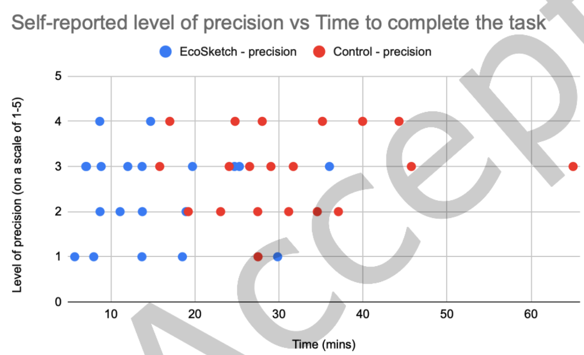

Fig. 10. Scatter plot of the relationship between time to complete the LCA and precision of the input data. Observable clusters of EcoSketch vs. control users suggest that relieving conventional tools' requirement to input precise data may help contribute to time savings

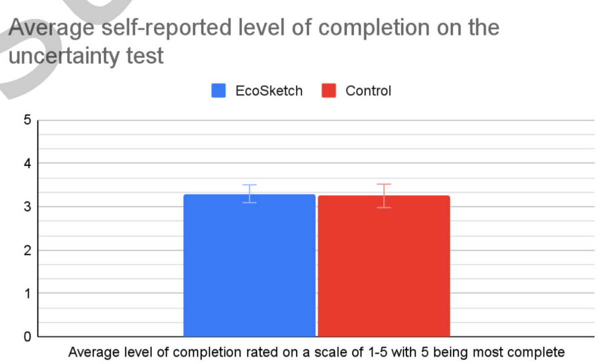

Fig. 11. Average level of model completion that users of EcoSketch (left) vs. users of the control LCA tool (right) were able to achieve during the study session

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 the modeling results.

6 DISCUSSION

To enable assessment of environmental impacts during early stages of product development, this research has explored the iterative, user-centered development of novel informatics software that supports more lightweight yet reliable LCA analyses. Specifically, our tool, EcoSketch promotes quick learnability, efficient completion of LCAs, intuitive visualizations, and the ability to explore eco impacts even when precise product details are still uncertain.

Developing EcoSketch involved a variety of both technical and human-centered challenges, including the formation and maintenance of meaningful partnerships between our academic lab and our industry collaborators, as part of understanding real-world needs and iteratively refining and testing solutions. By describing our design process and associated insights in this paper, we aimed to provide guidance for other researchers and practitioners aiming to more deeply integrate sustainability into product development. Our specific contributions include:

- A series of design requirements based on actual practitioner perspectives that are important to consider and satisfy when developing user interfaces to assist in sustainable design decision-making.
- A functional, interactive life cycle assessment tool tailored to enabling non-expert users to conduct environmental impact assessments during the early stages of product development.
- Findings from a between-subjects study that evaluated this tool using qualitative, semi-quantitative, and quantitative evaluation methods.
- A discussion that highlights a variety of important avenues for future collaboration between HCI researchers and industry practitioners to continue advancing the development of digital tools for systems-level sustainability efforts.

In the following subsections, we reflect on the tangible effects our approaches can have on real-world PD practices, synthesize our results into reusable design recommendations, and call out specific future opportunities based on insights from our development and evaluation of EcoSketch. Further speaking to our third research question around ways to build bridges between HCI and sustainable product design, we particularly highlight a variety of opportunities for collaboration between HCI researchers and sustainability practitioners to develop human-centered digital tools and methods tailored to the context of industrial-level environmentalism.

6.1 Translating early-stage LCA approaches into real-world PD practices

Results detailed in section 5.2 show how our new workflow, which enables uncertainty input, can improve the efficiency of performing LCAs with limited data in the early stages of PD. These efficiency gains mean that tools like EcoSketch are more readily usable in a fast-paced PD context. In fact, ongoing engagement with our industry partners provide multiple examples of how these approaches translate into tangible sustainability benefits in real-world PD projects.

First, consider a coffee maker redesign project conducted at Synapse, wherein the early use of LCA led to environmental impact reductions. Preliminary LCA results from EcoSketch directed designers' attention to the impacts from energy use of the "keep warm" function, leading to a focus on optimizing that feature in the redesign. However, prior to performing the LCA, the team erroneously assumed that the biggest impacts might come from the plastic housing of the coffee maker, and subsequent redesign steps would have focused on changing aspects of the product that would not have actually led to significant sustainability gains. In the absence of accessible tools like ours that are quick to learn and use, practitioners are unable to make time for traditional LCA in early-stage PD and may therefore make misguided eco-design decisions. Figure 12 illustrates this analysis. The visualization

Fig. 12. Example from Synapse of how applying LCA in early-stage PD can produce otherwise-unrealized insights and environmental impact improvements

has been graphically remade for corporate promotional materials, with design uncertainties reflected as a blur at the end of each bar on the chart.

In the case of the coffeemaker, a single area of focus for reducing impacts was identified through preliminary LCA. A second example highlights a more complex project involving the development of a handheld electronic flossing device (Figure 13). Here, having the ability to conduct preliminary LCA helped designers realize the benefits of pursuing multiple sustainable design avenues. Specific enhancements included limiting the use of air freight to reduce transportation impacts, making the charger out of recycled materials, and selecting contract manufacturers who use renewable energy among others. Together these strategies reduced overall eco-impacts by nearly 40%.

These examples illustrate the importance of considering environmental sustainability early-on in PD, when both environmental and economic costs of a product get locked in. Tools like EcoSketch provide practitioners insight into where the biggest opportunities to improve sustainability exist.

6.2 Design implications and guidelines

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 improved error recovery. Table 1 summarizes a list of unique features informed by user feedback, as well as the target needs they address, using valuable design aspects identified.

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

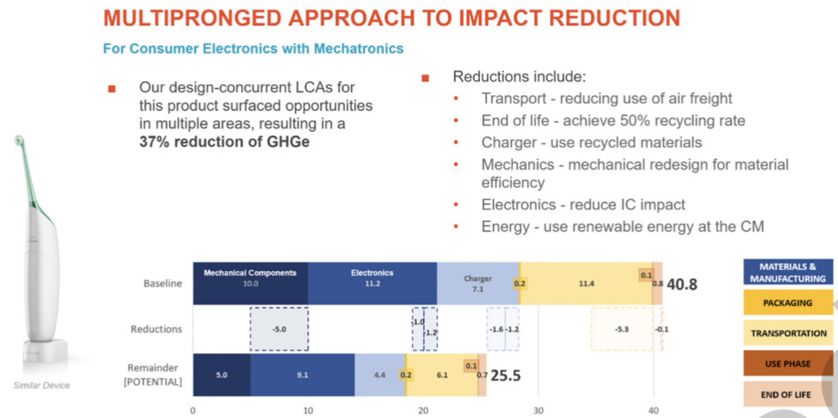

Fig. 13. Example from Synapse of how early-stage LCA can help designers realize multiple avenues and product development choices for enhancing sustainability impacts

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 (i.e., selecting a bar on a visualized graph brings users back to the relevant input field in the model-making page). 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.

Tying together these insights while keeping in mind the qualitative user feedback listed in Section 5.1, we propose the following generalizable design guidelines for HCI researchers developing sustainability tools for industry use:

- As environmental impacts modeling like LCA becomes more prevalent in industry, it is important to pursue efficient ways to quantify uncertainty in data, leading to more valid estimations and comparisons of impacts.
- In order to improve usability, tools must meet practitioners where they are. This means aligning terminology and model structures with familiar concepts, rather than using LCA-specific jargon and structures. It also means predicting the types of errors that novice users will make as they learn LCA, and supporting graceful recovery and continued use.
- It is critical to design visualizations that better support efficient practitioner decision-making without requiring expertise in environmental science. Effectively representing uncertainty is one challenge in the space.

6.3 Opportunities for HCI researchers building sustainability tools for industry

We believe our research illustrates how HCI researchers and developers can do 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 [9].

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 [18], 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 material extraction, 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 [2].

6.3.1 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 [17], and address chemical safety data gaps[15]. Machine learning and other digital 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 [51].

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 non-technical 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 [11]. 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. 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.

6.3.2 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. [27]

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 [43]. 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.

6.4 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. Our 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 Product Development and EarthShift Global, which will enable deeper study of the ways in which digital tools can support sustainable decision-making at the industrial level.

7 CONCLUSION

Our paper looks at topics addressed in SHCI literature, and identifies gaps that motivate the design of digital sustainability tools, specifically LCA tools, for industry use. The iterative human-centered design and development process of our tool, EcoSketch, aimed to address this opportunity by focusing on making LCA applicable to early-stage product development and accessible to non-expert users. We then evaluated EcoSketch to test its usability, efficiency, and overall effectiveness to explore the viability of integrating our lightweight-LCA approach into a fast-paced industry setting. The specific contributions of this paper include: a functional, interactive life cycle assessment tool tailored to enabling non-expert users to conduct environmental impact assessments during the early stages of product development; findings from a between-subjects study that evaluated this tool using qualitative, semi-quantitative, and quantitative evaluation methods; and a discussion that surfaces various novel avenues for collaboration between HCI researchers and industry practitioners to continue advancing the development of digital tools for systems-level sustainability efforts.

REFERENCES

[1] Johannes Behrisch, Mariano Ramirez, and Damien Giurco. 2010. The Use of Ecodesign Strategies and Tools: State of the Art in Industrial Design Praxis, Comparing Australian and German Consultancies. In *Proceedings ERSCP-EMSU*. Delft, The Netherlands.

[2] Niki Bey, Michael Z. Hauschild, and Tim C. McAloone. 2013. Drivers and Barriers for Implementation of Environmental Strategies in Manufacturing Companies. *CIRP Annals* 62, 1 (Jan. 2013), 43–46. https://doi.org/10.1016/j.cirp.2013.03.001

[3] Isabella Bianco, Francesca Thiébat, Corrado Carbonaro, Simonetta Pagliolico, Gian Andrea Blengini, and Elena Comino. 2021. Life Cycle Assessment (LCA)-Based Tools for the Eco-Design of Wooden Furniture. *Journal of Cleaner Production* 324 (Nov. 2021), 129249. https://doi.org/10.1016/j.jclepro.2021.129249

[4] Eli Blevis. 2007. Sustainable Interaction Design: Invention & Disposal, Renewal & Reuse. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. Association for Computing Machinery, New York, NY, USA, 503–512. https://doi.org/10.1145/1240624.1240705

[5] Leonardo Bonanni, Matthew Hockenberry, David Zwarg, Chris Csikszentmihalyi, and Hiroshi Ishii. 2010. Small Business Applications of Sourcemap: A Web Tool for Sustainable Design and Supply Chain Transparency. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. Association for Computing Machinery, New York, NY, USA, 937–946. https://doi.org/10.1145/1753326.1753465

[6] Virginia Braun and Victoria Clarke. 2012. *Thematic analysis.* American Psychological Association.

[7] Christina Bremer, Bran Knowles, and Adrian Friday. 2022. Have We Taken On Too Much?: A Critical Review of the Sustainable HCI Landscape. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3491102.3517609

[8] john Brooke. 1996. SUS: A 'Quick and Dirty' Usability Scale. In *Usability Evaluation In Industry*. CRC Press.

[9] Tejaswini Chatty, Will Harrison, Hana H. Ba-Sabaa, Jeremy Faludi, and Elizabeth L. Murnane. 2022. Co-Creating a Framework to Integrate Sustainable Design into Product Development Practice: Case Study at an Engineering Consultancy Firm. *Sustainability* 14, 15 (Jan. 2022), 9740. https://doi.org/10.3390/su14159740

[10] Tejaswini Chatty, Yingkun Qu, Hana H. Ba-Sabaa, and Elizabeth L. Murnane. 2021. Examining The User Experience Of Life Cycle Assessment Tools And Their Ability To Cater To Ecodesign In Early-Stage Product Development Practice. *Proceedings of the Design Society* 1 (2021), 1441–1450. https://doi.org/10.1017/pds.2021.405

[11] Michael Correll and Michael Gleicher. 2014. Error Bars Considered Harmful: Exploring Alternate Encodings for Mean and Error. *IEEE Transactions on Visualization and Computer Graphics* 20, 12 (2014), 2142–2151. https://doi.org/10.1109/TVCG.2014.2346298

[12] Tawanna Dillahunt, Jennifer Mankoff, and Jodi Forlizzi. 2010. A proposed framework for assessing environmental sustainability in the HCI community. In *Examining Appropriation, Re-Use, and Maintenance of Sustainability workshop at CHI*.

[13] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the Landscape of Sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1975–1984. https://doi.org/10.1145/1753326.1753625

[14] Steve Easterbrook. 2014. From Computational Thinking to Systems Thinking: A Conceptual Toolkit for Sustainability Computing. In *ICT for Sustainability 2014 (ICT4S-14)*. Atlantis Press, 235–244. https://doi.org/10.2991/ict4s-14.2014.28

[15] Peter P. Egeghy, Linda S. Sheldon, Kristin K. Isaacs, Halûk Özkaynak, Michael-Rock Goldsmith, John F. Wambaugh, Richard S. Judson, and Timothy J. Buckley. 2016. Computational Exposure Science: An Emerging Discipline to Support 21st-Century Risk Assessment. *Environmental Health Perspectives* 124, 6 (June 2016), 697–702. https://doi.org/10.1289/ehp.1509748

[16] Jeremy Faludi and Alice Agogino. 2018. What Design Practices Do Professionals Use for Sustainability and Innovation?. In *Proceedings of the DESIGN 2018 15th International Design Conference*. https://doi.org/10.21278/idc.2018.0180

[17] Jeremy Faludi, Tina Hoang, Patrick Gorman, and Martin Mulvihill. 2016. Aiding Alternatives Assessment with an Uncertainty-Tolerant Hazard Scoring Method. *Journal of Environmental Management* 182 (Nov. 2016), 111–125. https://doi.org/10.1016/j.jenvman.2016.07.028

[18] Jeremy Faludi, Felix Yiu, and Alice Agogino. 2020/ed. Where Do Professionals Find Sustainability and Innovation Value? Empirical Tests of Three Sustainable Design Methods. *Design Science* 6 (2020/ed), e22. https://doi.org/10.1017/dsj.2020.17

[19] Rolf Frischknecht and Gerald Rebitzer. 2005. The ecoinvent database system: a comprehensive web-based LCA database. *Journal of Cleaner Production* 13, 13-14 (2005), 1337–1343.

[20] Jon Froehlich, Leah Findlater, and James Landay. 2010. The Design of Eco-Feedback Technology. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1999–2008. https://doi.org/10.1145/1753326.1753629

[21] Eva Ganglbauer, Wolfgang Reitberger, and Geraldine Fitzpatrick. 2013. An Activist Lens for Sustainability: From Changing Individuals to Changing the Environment. In *Persuasive Technology (Lecture Notes in Computer Science)*, Shlomo Berkovsky and Jill Freyne (Eds.). Springer, Berlin, Heidelberg, 63–68. https://doi.org/10.1007/978-3-642-37157-8_9

[22] Dr Paul Griffin. 2017. *CDP Carbon Majors Report 2017*. Technical Report. 16 pages.

[23] Brage B. Hansen, Marlène Gamelon, Steve D. Albon, Aline M. Lee, Audun Stien, R. Justin Irvine, Bernt-Erik Sæther, Leif E. Loe, Erik Ropstad, Vebjørn Veiberg, and Vidar Grøtan. 2019. More Frequent Extreme Climate Events Stabilize Reindeer Population Dynamics. *Nature Communications* 10, 1 (April 2019), 1616. https://doi.org/10.1038/s41467-019-09332-5

[24] Tomoko Hasegawa, Gen Sakurai, Shinichiro Fujimori, Kiyoshi Takahashi, Yasuaki Hijioka, and Toshihiko Masui. 2021. Extreme Climate Events Increase Risk of Global Food Insecurity and Adaptation Needs. *Nature Food* 2, 8 (Aug. 2021), 587–595. https://doi.org/10.1038/s43016-021-00335-4

[25] Mike Hazas, A. J. Bernheim Brush, and James Scott. 2012. Sustainability Does Not Begin with the Individual. *Interactions* 19, 5 (Sept. 2012), 14–17. https://doi.org/10.1145/2334184.2334189

[26] Kiley Jacques. 2022. BEAM Estimator for Measuring Embodied Carbon. https://www.greenbuildingadvisor.com/article/beam-estimator-for-measuring-embodied-carbon.

[27] Florian A. Jaeger, Peter Saling, Nikolaj Otte, Rebecca Steidle, Jan Bollen, Birte Golembiewski, Ivana Dencic, Ulla Letinois, Torsten Rehl, and Johannes Wunderlich. 2022. Challenges and Requirements of Exchanging Product Carbon Footprint Information in the Supply Chain. *E3S Web of Conferences* 349 (2022), 07005. https://doi.org/10.1051/e3sconf/202234907005

[28] Jesper Kjeldskov, Mikael B. Skov, Jeni Paay, and Rahuvaran Pathmanathan. 2012. Using Mobile Phones to Support Sustainability: A Field Study of Residential Electricity Consumption. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. Association for Computing Machinery, New York, NY, USA, 2347–2356. https://doi.org/10.1145/2207676.2208395

[29] Bran Knowles, Oliver Bates, and Maria Håkansson. 2018. This Changes Sustainable HCI. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174045

[30] E. Krahmer and N. Ummelen. 2004. Thinking about Thinking Aloud: A Comparison of Two Verbal Protocols for Usability Testing. *IEEE Transactions on Professional Communication* 47, 2 (June 2004), 105–117. https://doi.org/10.1109/TPC.2004.828205

[31] Jim Lindberg, Alison Frazee, Lori Ferriss, and Larry Strain. 2022. Calculating Carbon Savings from Building Reuse and Retrofit.

[32] M. Margallo, R. Dominguez-Ramos, and A. Aldaco. 2019. Incorporating Life Cycle Assessment and Ecodesign Tools for Green Chemical Engineering: A Case Study of Competences and Learning Outcomes Assessment. *Education for Chemical Engineers* 26 (Jan. 2019), 89–96. https://doi.org/10.1016/j.ece.2018.08.002

[33] M. Meursing. 2015. *Sustainability Inspired Materials Selection App for Designers.* Master of Science in Integrated Product Design. Faculty of Engineering Design Engineering at TU Delft, Delft, The Netherlands.

[34] Jakob Nielsen. 1994. Enhancing the explanatory power of usability heuristics. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. 152–158.

[35] Maria Normark and Jakob Tholander. 2014. Performativity in Sustainable Interaction: The Case of Seasonal Grocery Shopping in Ecofriends. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. Association for Computing Machinery, New York, NY, USA, 271–280. https://doi.org/10.1145/2556288.2557318

[36] Elsa Olivetti, Siamrut Patanavanich, and Randolph Kirchain. 2013. Exploring the Viability of Probabilistic Under-Specification To Streamline Life Cycle Assessment. *Environmental Science & Technology* 47, 10 (May 2013), 5208–5216. https://doi.org/10.1021/es3042934

[37] L. G. Pereira, O. Cavalett, A. Bonomi, Y. Zhang, E. Warner, and H. L. Chum. 2019. Comparison of Biofuel Life-Cycle GHG Emissions Assessment Tools: The Case Studies of Ethanol Produced from Sugarcane, Corn, and Wheat. *Renewable and Sustainable Energy Reviews* 110 (Aug. 2019), 1–12. https://doi.org/10.1016/j.rser.2019.04.043

[38] A. T. D. Perera, Vahid M. Nik, Deliang Chen, Jean-Louis Scartezzini, and Tianzhen Hong. 2020. Quantifying the Impacts of Climate Change and Extreme Climate Events on Energy Systems. *Nature Energy* 5, 2 (Feb. 2020), 150–159. https://doi.org/10.1038/s41560-020-0558-0

[39] Chris Preist, Daniel Schien, and Eli Blevis. 2016. Understanding and Mitigating the Effects of Device and Cloud Service Design Decisions on the Environmental Footprint of Digital Infrastructure. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 1324–1337. https://doi.org/10.1145/2858036.2858378

[40] Chris Preist, Daniel Schien, and Paul Shabajee. 2019. Evaluating sustainable interaction design of digital services: The case of YouTube. In *Proceedings of the 2019 CHI conference on human factors in computing systems*. 1–12.

[41] Barath Raghavan and Daniel Pargman. 2017. Means and Ends in Human-Computer Interaction: Sustainability through Disintermediation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 786–796. https://doi.org/10.1145/3025453.3025542

[42] Amina Razvi. 2021. Introducing the New Higg Product Module: Designing with Sustainability and Circularity in Mind. https://apparelcoalition.org/introducing-the-new-higg-pm/.

[43] Erin Rovalo, John McCardle, Ethan Smith, and Gretchen Hooker. 2020. Growing the Practice of Biomimicry: Opportunities for Mission-Based Organisations Based on a Global Survey of Practitioners. *Technology Analysis & Strategic Management* 32, 1 (Jan. 2020), 71–87. https://doi.org/10.1080/09537325.2019.1634254

[44] J. E. Shigley, L. D. Mitchell, and H. Saunders. 1985. Mechanical Engineering Design (4th Ed.). *Journal of Mechanisms, Transmissions, and Automation in Design* 107, 2 (June 1985), 145–145. https://doi.org/10.1115/1.3258702 arXiv:https://asmedigitalcollection.asme.org/mechanicaldesign/article-pdf/107/2/145/5935813/145_1.pdf

[45] M. Six Silberman, Lisa Nathan, Bran Knowles, Roy Bendor, Adrian Clear, Maria Håkansson, Tawanna Dillahunt, and Jennifer Mankoff. 2014. Next Steps for Sustainable HCI. *Interactions* 21, 5 (Sept. 2014), 66–69. https://doi.org/10.1145/2651820

[46] Jing Tao, Zhaorui Chen, Suiran Yu, and Zhifeng Liu. 2017. Integration of Life Cycle Assessment with Computer-Aided Product Development by a Feature-Based Approach. *Journal of Cleaner Production* 143 (Feb. 2017), 1144–1164. https://doi.org/10.1016/j.jclepro.2016.12.005

[47] Melissa Tensa, Jenna Wang, Roscoe Harris, Jeremy Faludi, and Bryony DuPont. 2021. A Study of Graphical Representations of Uncertainty in LCA Guide: 23rd International Conference on Engineering Design, ICED 2021. *Proceedings of the Design Society* 1 (2021), 253–262. https://doi.org/10.1017/pds.2021.26

[48] Noelle Walsh. 2020. Microsoft Sustainability Calculator Helps Enterprises Analyze the Carbon Emissions of Their IT Infrastructure. https://azure.microsoft.com/en-us/blog/microsoft-sustainability-calculator-helps-enterprises-analyze-the-carbon-emissions-of-their-it-infrastructure/.

[49] Ben A. Wender, Rider W. Foley, Troy A. Hottle, Jathan Sadowski, Valentina Prado-Lopez, Daniel A. Eisenberg, Lise Laurin, and Thomas P. Seager. 2014. Anticipatory Life-Cycle Assessment for Responsible Research and Innovation. *Journal of Responsible Innovation* 1, 2 (May 2014), 200–207. https://doi.org/10.1080/23299460.2014.920121

[50] Gregor Wernet, Christian Bauer, Bernhard Steubing, Jürgen Reinhard, Emilia Moreno-Ruiz, and Bo Weidema. 2016. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment* 21, 9 (2016), 1218–1230.

[51] Antony J. Williams, Christopher M. Grulke, Jeff Edwards, Andrew D. McEachran, Kamel Mansouri, Nancy C. Baker, Grace Patlewicz, Imran Shah, John F. Wambaugh, Richard S. Judson, and Ann M. Richard. 2017. The CompTox Chemistry Dashboard: A Community Data Resource for Environmental Chemistry. *Journal of Cheminformatics* 9, 1 (Nov. 2017), 61. https://doi.org/10.1186/s13321-017-0247-6

[52] Max Willis, Julian Hanna, Enrique Encinas, and James Auger. 2020. Low Power Web: Legacy Design and the Path to Sustainable Net Futures. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3334480.3381829