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WHERE NEXT?: EXPLORING OPPORTUNITY AREAS AND TOOL FUNCTIONS FOR SUSTAINABLE PRODUCT DESIGN

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ABSTRACT

Shifts in policy and consumers' awareness have raised the importance of sustainability in product design, inspiring the development of tools that support more sustainable design. However, such tools are not adopted as quickly as expected. To understand what tools designers consider useful, we explored how much control designers perceive over existing design strategies, and how much impact they think these strategies have. We used a survey (n=42) and follow-up interviews (n=12) to ask hardware product design professionals what areas they see opportunities in, and what functions they look for in tools. The findings reveal that designers perceive impact and control differently in different opportunity areas, so to increase the likelihood of adoption, tools should incorporate features that reflect those differences. Designers report the least control over aspects related to manufacturing, and also rate these as having low impact on sustainability. In contrast, designers attribute high control and impact to aspects related to their design practice and their organizations business model, which are tightly linked. To address these issues, designers pointed towards tools that improve information transparency, support decision-making, predict results, share knowledge, and discover user needs. Regardless of how much control designers have, they care about tools and strategies that are highly impactful.

1 INTRODUCTION

Each year new policies are enacted mandating sustainable production, and consumers increasingly want the products they purchase to be more environmentally sustainable. These policy and market shifts pose new opportunities for product designs teams to rethink their business models, and will change the way designers work [1]. Yet in the pursuit of successful hardware product design, requirements such as cost, customer appeal, and performance often outweigh sustainability [2]. Lack of regulation and standards [3], less mature sustainable supply chains [4], and underdeveloped green business models [5] make

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it even harder for designers to prioritize sustainable goals in their practice. Additionally, some existing practices are counter productive to sustainability efforts. For example, many hardware products are “planned for obsolescence” [6, 7], with purposely frail designs that artificial limit useful life so that consumers will buy more products more often, consequentially increasing the amount of resources needed and waste generated by and for these products. The global material footprint has increased by 70% between 2000 and 2017, and electronics waste continues to proliferate - only 20% of materials are properly recycled [8]. This is especially problematic considering that recycling is the most commonly discussed R-strategy [9]. It also highlights how individual efforts made during product design can still significantly affect the economic viability of recycling end-of-use products [10] despite competing with system structures like the recycling industry’s volatile nature, dependency on international factors, and financial difficulties [11].

Efforts to prioritize sustainability are particularly challenging since sustainability is such a dynamic and complex topic. To help designers balance sustainability among other existing constraints and requirements, researchers and developers have introduced sustainability-focused software tools. For example, life cycle assessment tools help designers evaluate the sustainability outcomes of their products by providing them with environmental impact data, such as carbon emission and water usage [12]; manufacturing and supply chain tools have been developed to guide designers to make more sustainable material and process choices [13, 14]; product passport tools provide more information for stakeholders and consumers during product recycling and reuse [15]. In an effort to improve the adoption of such tools, research on persuasive interfaces have investigated the use of design patterns to guide users in making more sustainable choices [16, 17]. In addition, studies have compared the performance and accuracy of different tools to investigate functionality of tools across different regions [18, 19].

Prior research has shown that design tools are often developed in isolation, without a detailed understanding of actual industrial practices and context [20], historically resulting in low adoption rates by industry practitioners [21]. Further confounding efforts to prioritize sustainability in design is ambiguity on what factors designers have control over and the impact of these decisions on sustainable design outcomes. In other words, do designers even consider sustainable design tools as compatible with their current design practices?

In our work, we want to learn from professional designers about what future opportunities they see for sustainable tool development. To study this, it is important to understand what decisions they are able to make to influence their design’s sustainability (control), and how much their actions influence the sustainability of their designs (impact). We use perceived control and impact as two axes, and ask the following two research questions:

1. What areas do designers recognize as opportunities to increase their control and impact?
2. What tools can help designers increase the sustainability of their designs?

To address these research questions, we conducted an online survey and a follow-up interviews with professional hardware designers. The results of our study reveal that designers identify different tools for different opportunities. They are most interested in tools that appeal to aspects related to design practice, business models, and manufacturing. Tool features that they suggest would increase their control and impact are those that improve information transparency, support decision-making, predict results, share knowledge, and discover user needs. Overall, our findings suggest that perceived control and impact are two important axes that can future guide tool development.

2 RELATED WORK

2.1 The Impact of Sustainable Design Practices

Sustainability is a broad term that often includes economical, environmental and social aspects. In this paper, we focus mainly on the environmental aspect: how do design practices affect the earth and its ecosystem? In other words, how much impact does design have on the environment, and consequently, how much impact do sustainable design strategies have on the environment? Assessing impact can be an intensive process that requires careful screening and scoping with different stakeholder, identifying trade-offs, and proposing mitigation measures requires expertise in sustainability and take nontrivial focus [22, 23]. Sustainability impact assessment helps to address important governance challenges by using data to support policy and trade decision making [24]. The impact of design practice on sustainability can also be difficult to assess because design involves numerous trade-offs [25]. The assessment process ensures the overall impact of a product is correctly assessed. To give an example in consumer electronics, many smartphones use strong adhesives to secure critical parts such as the battery. On one hand, this design practice helps extend the product lifetime since the phone can be robust against accidental drops. On the other hand, the adhesive makes it difficult to take out the battery, thus impeding efforts to repair, upgrade, and recycle the phone. So how much impact does this design decision have?

Besides trade-offs within the same product, regions and product types can also influence how impactful a strategy is on the product’s sustainability. For example, one of the biggest impact on many consumer electronics is energy consumption [26]). In a region where energy production is mostly renewable, this would be less of an issue than in places that use less sustainable methods. Another issue is that design intent does not equal impact. It is possible that a product is designed to be more sustainable but ends up becoming less sustainable due to how it interacts in the world. For example, technological advancements of display screens that reduce or eliminate energy consumption when the device is idle can be countered by user habits which require the device to be on [27].

As we see, there is no single measure or assessment of how design strategies can impact sustainability. Guiding designers towards more sustainable and impactful decisions while balancing other requirements will require substantial efforts. Software tools can help accelerate this shift by supporting designers to make more sustainable choices throughout the design process.

2.2 Tools for Sustainable Product Design

Sustainability is growing in importance, and researchers and developers have developed many tools to guide the development of sustainable products [28, 29]. However, software adoption requires more than its existence for people to adopt it [21]. The below section summarizes various methods and tools that have been developed to support product designers.

Substantial efforts have been undertaken to develop more sustainable business models [30] and the organizational barriers and enablers related to the adoption of these business models [31]. Similarly, work has been done to develop design methods that integrate environmental impacts into existing design practices and approaches [28, 29], since designers cannot prioritize what is not salient during decision-making.

The demand for more systematic methods that incorporate sustainability in design decision-making has led to the development of commercially available tools such as SimaPro, openLCA, Gabi that support these priorities during the design process [32]. Other tools aim to provide better information for designers around supply chain [33], materials [13] and manufacturing [34]. Inventor Eco material advisor and Granta material database are commercially available tools to guide designers' selection of sustainable materials [35]. Other tools provide more evaluative information to help designers predict environmental impacts of generated solutions to guide decision making [36]. Examples of such tools are life-cycle assessment tools [28], The House of Ecology [37] and Quality Function Deployment [37].

To improve the efficiency of tools, research has investigated the design patterns that can encourage desirable user behaviors [38]. For example, persuasive interface research seeks to design interventions such that they are more impactful [16], such as by guiding users to use energy more efficiently [17] and selecting more sustainable materials [39]. Researchers have also compared the outcomes of tools [40], and functionalities of tools for different regions [19]. Since designers must address trade-offs as they incorporate sustainability into their designs, some researchers have investigated how to better handle trade-offs in sustainable design tools [13].

To summarize, much work has been done to develop methods and tools to encourage more sustainable decisions. However, questions still exist around how designers actually engage and interact with such tools, as well as how they prioritize sustainability during design activities. For example, it is unclear how much control designers really have over their decisions, and how much impact they perceive these decisions have on the sustainability of their products. The purpose of this work is to investigate what designers think about several existing sustainable design strategies using the lens of control and impact.

3 Method

We recruited survey participants through Autodesk Technology Center Group, Autodesk Mechanical CAD User Group, and a US hardware incubator Slack group in July and August 2021. Together, these groups have approximately 1300 members. We conducted our survey on Qualtrics [41]. Among 88 people who started the survey, 44 completed it. We excluded 2 who described experiences that were not in hardware products, resulting in 42 participants for our data analyses. Of those, 21 participants indicated interest in the follow-up interviews, but only 12 actually went through with participating in the interviews. On average, the survey took around 15 minutes to complete, and the interviews lasted between 20-30 minutes.

3.1 Survey Questions

3.1.1 Participant Background

We first asked demographic questions like the participants' educational background, the number of years of experience with designing hardware products, their primary role in their organization, the size of the organization they work for, and the country they are based in. We did not request age and gender to protect the privacy of the participants [42].

To understand the participants' experience, we asked them to describe several hardware products they contributed to during design and development. To encourage richer and more detailed responses about their experience, we asked participants to focus on only a single design project for this survey.

3.1.2 Grouping Sustainable Design Strategies

We selected 12 previously established sustainable design strategies [43, 44] for designers to group into high/low control and impact. The strategies used are: Increase product lifetime, Support easy repair, Support easy repair, Support easy upgrade, Support reuse and remanufacturing, Standardize components and improve compatibility, Select cleaner, renewable, and/or recycled materials, Reduce total amount of materials in the product and its packaging, Improve material recovery, i.e. recyclability, Reduce total energy consumed during production and usage, Reduce water usage during production, Source local materials and labor to minimize transportation, and Protect human health during production and usage. We pilot tested these strategies with two designers to ensure clarity before the survey.

The participants were shown two grouping activities, one for control and one for impact. Each activity asked the participants to choose the four strategies they believed to have the most (and the least) control over or have the most impact on sustainability, and rank them. For example, we asked "How much **control** do you and your team have over the following sustainability factors during design and development?". The participants could then assign up to four strategies in a bucket of "a lot of control" and up to four into a bucket of "little or no control". They could then rank these choices within each bucket. Only focusing on the most and least helps identify which strategies participants feel more confident about.

3.1.3 Opportunity Areas

After the grouping activity, we asked participants to elaborate on their responses. For example, we asked 1) "Pick one factor that you put into 'a lot of control'. Could you explain why you have a lot of control over this factor?", and 2) "Pick one factor that you put into 'little or no control'. Could you explain why you have little or no control over this factor?". After grouping impact, we asked: 1) "Pick one factor that you put into 'most impact'. Could you explain why you find this factor more impactful?", and 2) "Pick one factor that you put into 'least impact'. Could you explain why you find this factor less impactful?". These questions allow us to identify opportunity areas from our qualitative data analysis (see Section 3.3).

3.1.4 Tool Suggestions

Additionally, we asked participants to provide suggestions on resources and tools that may help them to better incorporate sustainability in their design practice. For control, we asked "Pick one factor that you put into 'little or no control'. What are some tools and resources that could increase your control over this factor?". For impact, we asked "Pick one factor that you think is impactful. What are some tools and resources that made you feel this way?". Lastly, we asked participants to tell us "Generally speaking, what are some tools and resources that could make it easier for you to incorporate sustainability in your practice?". Together, these questions enable participants to provide solutions that they think would work for them and their situation. From their responses, we can also learn what problems they are most interested in solving.

At the end of the survey, we asked participants to share additional thoughts and leave their contact information if they are interested in follow-up interviews, future research opportunities, and updates.

3.2 Follow-up Interviews

We followed up with 21 survey respondents who indicated interest in participating in interviews. 12 scheduled interviews with us. We conducted and recorded the interviews on Zoom during August 2021. We reimbursed participants with 35 US dollar gift card for their time. During the interview, we invited the participants to elaborate on their survey responses by sharing detailed examples from their practice. The interview also included a brainstorming activity in which we asked participants to describe the kind of tools they would develop if they were given 1 million US dollars. This ideation prompt allowed for the research team to explore the space of potential solutions with participants in an open-ended to unstructured manner.

3.3 Qualitative Data Analysis

To analyse the open-ended survey questions and interview transcripts, two researchers individually coded themes in each participant's responses. Then, these themes were collaboratively discussed and consolidated into several higher order coding categories. To better discuss these coding categories, the categories were grouped into either an "opportunity area" (see Table 1) or a "tool function" (see Table 2).

Opportunity Areas

Code category	Example quote
Business Model	"Design for repair is not a value in premium consumer electronics." (P11)
Organization	"The company was very small and struggling to sell enough units, so making it more sustainable was an afterthought that we did not have enough time to focus on." (P15)
Design Practice	"The entire product can be disassembled with a few hex keys." (P6)
Regulation	"Legislation for recycling and disassembly as EU is doing." (P21)
Material Supplier	"Better availability of post-consumer recycled materials, and more experience among our suppliers on using those materials." (P10)
Manufacturing	"If factories could advise on techniques used to perform certain functions (like attaching parts or preparing pieces) and teach designers how to optimize for sustainability best practices." (P1)

TABLE 1. An overview of opportunity area categories and an example quote that illustrates the coding category.

Tool Function

Code category	Example quote
Improve Transparency	"Better visibility into life cycle energy cost of various manufacturing processes may help guide process or vendor selection" (P17)
Search Options	"Given a list of materials that we can choose from that are more easily recovered and recycled, we'd be able to pick one knowing there's a chance it could be recycled. Currently, with so little cost-effective recycling going on, it's hard to know what is realistically recyclable. Even though technically any thermoplastic has a chance." (P12)
Discover Users	"Product lifetime is crucial as analysed from journey mapping and empathy study." (P41)
Share Knowledge	"A library of examples would be helpful - examples that have been tried successfully." (P8)
Predict Results	"A tool that could show me the greenhouse-gas footprint of my design, through the entirety of the supply chain - from actually making the raw resins, PCBs, PCBAs, plastic molding, metal stamping, etc. (product build) as well as the packaging build, through to shipping of the product (by air or by ship) from original factory to distribution centre(s) to end customers. Seeing that greenhouse-gas map along the value-creation journey would be fascinating and useful." (P22)

TABLE 2. An overview of tool suggestion categories and an example quote that illustrates the coding category.

4 FINDINGS

We first present details about participants' demographic and work experience in order to provide the necessary context for their responses regarding the role of sustainability in their design practice. Next, we explore the designers' sense of control and impact of sustainable design decisions to address each research question, using the qualitative data from the surveys and interviews to provide insight into the participants responses. The characteristics of the interview participants mirror those of the survey participants in the sense that the interview participants were fairly representative of the participants a whole.

4.1 Demographics

The majority of the survey participants work in North America, with 64% from the United States and 9% from Canada. The second largest region is Europe, with participants from Netherlands, United Kingdom, Germany, Ukraine, Italy, and Bulgaria making up 19% of the total survey participants. The remaining 7% are from India and Venezuela.

36 out of 42 participants shared their educational background. Among them, most of them hailing from an Engineering (75%) or Design (16%) background.

4.2 Work Experience

Following typical company size categorization schemes, we found that 33% of the participants work in micro enterprises (1 to 9 employees), 19% in small (10 to 49 employees), 18% in medium (50 to 249 employees), and 29% in large companies (more than 250). Combining these into smaller (micro and small) and larger companies (medium and large) results in a fairly even split of participants.

More than a quarter of the participants have more than one role. Two thirds of all participants are active in managerial roles such as founders, engineering managers or product managers. Half of the participants work on the engineering side of product development while one fifth are in design.

The participants have an average of 13 years (standard deviation of 8) of experience designing hardware products, with 25% of the participants having less than 5 years of experience, and 25% having more than 20 years.

The participants showcased a wide range of products: 21% discussed consumer electronics, such as laptops and smart watches. 19% chose machinery, such as Computer Numerical Control (CNC) machines and 3D printers. 17% chose Internet of Things, such as monitoring systems and earthquake sensors. The remaining is spread across robotics, medical devices, instruments (e.g. mass spectrometer), automobile (e.g. electrical vehicle charger), home appliances, and aerospace (e.g. propulsion engine).

4.3 RQ1: What Areas Do Designers Recognize As Opportunities To Increase Their Control And Impact?

To understand what factors contribute to the designers' perception of control and impact, we asked participants to explain why they have high or low control over a strategy, and why a strategy has high or low impact on sustainability (see Section 3.1.2).

The themes that emerged from the participants' responses can be grouped into six categories that relate to various aspects of design practice (see Table 1): regulation, manufacturing, material suppliers, organization, business model and design practice (for details on the analysis see Section 3.3). Figure 1 shows how these themes relate to the designers' feelings of control and impact. Low control and impact was frequently attributed to manufacturing, which designers consider to be beyond their visibility and responsibility. In contrast, design practices and business models are within designers' control, and are tightly connected. Together they influence designers' sense of impact on sustainability outcomes the most.

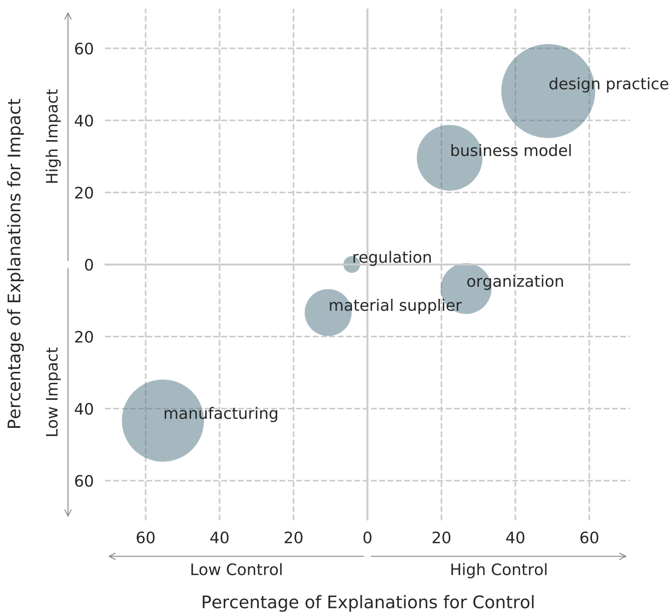

FIGURE 1. The opportunity areas that designers discussed when explaining their groupings for control and impact. The size of the circle corresponds to the number of times this opportunity area was mentioned, while the axis indicate how often this opportunity area was mentioned in relation to how much control (horizontal x-axis) and impact (vertical y-axis).

4.3.1 Low Control and Impact Areas Around half of the explanations for low control and for low impact were related to Manufacturing. The participants describe several reasons for listing manufacturing as contributing to feelings of low control and impact. In general, participants encounter lack of transparency into manufacturing processes and high barriers to information access. For many, manufacturing was considered to be beyond the designer's responsibility because it is not in-house. P40 described clear boundaries between responsibilities: *"What happens in factories is hard to control, but choosing one production technique over another is still within our control and contributes differently to environmental impact"*. Lack of local manufacturers, and thus viable alternatives, also contributes to feelings of low control. P23 describes the dilemma as such *"If we sourced local labour, we'd have to build a Printed Circuit Board fabrication in Canada at great expense and environmental cost!"*. Lack of control or insight into manufacturing processes, especially over larger geographical distance was also cited: *"Protect human health during production and usage: ... some of the parts are made in far of places which we are unable to monitor or control"* (P6).

4.3.2 High Control and Impact Areas Design practices play a big role in designers' sense of control and impact. In a third to half of the cases, participants used their existing design practice to justify their groupings of low control, high control, and high impact. Participants almost uniformly referred to increasing product lifetime as a high impact strategy (*"Making products last longer means fewer products need to be made, which helps on basically every area of sustainability"* (P10), while referring to other strategies for how to achieve the goal of increasing product lifetimes. As described by P6: *"We put a lot of effort into ensuring a life time of at least 30 years with minimal maintenance needed in between. This is achieved by using materials and surface treatments that can stand the environmental and mechanical impact. Using clever mechanical constructions. When maintenance is required it should be safely, quick and easy to implement"*. This relationship between the control over the strategy and its impact on sustainability appears to be quite close: *"making the design as reliable as possible increases the amount of time the product can be used"* (P19). However, this can differ between product types. P23 described how the repairability strategy would not apply to their product, and therefore thinks that a different strategy would have more impact: *"because the product is basically a circuit board that is hard to modify after production, extending the lifetime of the product is the most likely to have an impact as we will require fewer of them overall through the product life cycle"*. Some participants assigned low impact to a sustainable design strategy when they have already implemented it, arguing that any additional effort would result in relatively lower returns: *(*P6). Thus, it would seem that participants were primarily looking for new strategies to implement that would yield high impact benefits to sustainability, as they believed that existing processes were often already optimized.

Business models contribute to high impact and high control. Around one fourth of the participants referred to their organization's business model as the reason for having high control or impact, particularly when these were in line with the sustainability strategies. For example, P22 described that they had more design freedom if they could justify their actions as providing value for the client: *"We can directly impact increase product lifetime by creating design acceptance criteria and testing; this is easy to justify and resource internally, as a higher quality product is a goal, and longevity is a direct customer benefit"*. P26 contends that this also applies to reducing development costs: *"Standardizing components is also a trick for reducing cost so anytime we can offer that it can be an easier sell than other items"*. Some participants, such as P38, took this even further by saying that sustainability was their unique selling point *"Reduce total energy consumed during usage is the only reason we manufacture our products, to decrease energy usage"*. However, for most participants, sustainability was a nice bonus: *"By reducing the amount of waste we produce, upcycling can become less of a requirement and more of an added benefit to a sustainable business"*(P34).

Design practices and business models are tightly coupled. Business models shape how designers practice. It is easier to implement a design strategy when it aligns with existing business models: *"Increasing product lifetime gives the best customer experience related to electric vehicles and accelerates their adoption. And essentially extends the life of the vehicle for given initial CO2 input"* (P28). The stronger the alignment, the better: *"Designing for upgradeability was the core differentiator for our product, so we start the architecture with it in mind"* (P10). Conversely, when there is a disconnect between the designers' practice and the company's business model it is more difficult to implement a sustainable design strategy, even if the designers would want to do so: *"Supporting easy upgrade is very difficult when product is cemented permanently in the ground"* (P24).

4.4 RQ2: What Tools Can Help Designers Increase The Sustainability Of Their Designs?

We asked participants to provide ideas for tools and resources that might help them increase their control over a strategy and understand the impact of a strategy over sustainable outcomes. The emerging themes were grouped into five categories that correspond to the various tool functions and features that participants would like to see (for coding details and code categories see Section 3.3): Improve Transparency, Search Options, Discover Users, Share Knowledge, and Predict Results (see Table 2). Figure 2 shows how often the participants suggested each type of tool function. In many cases, the tools that participants suggested overlap with or address some of the opportunity areas described in section 4.3. For example, to counter the lack of transparency into manufacturing processes and their impact on sustainability, participants are looking for tools that can improve information access and support decision-making (see Section 4.4.1). Moreover, to better compare or evaluate decisions, participants would like tools that can simulate and predict results (see Section 4.4.2). To increase adoption of sustainable practices, participants want the ability to share knowledge and discover user needs by connecting with fellow practitioners and users, and tools could either low or high control situations, as long as they were high in impact (see Section 4.4.3).

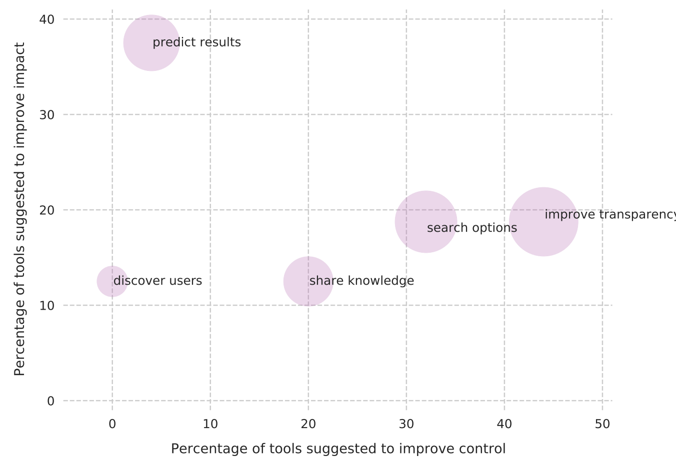

FIGURE 2. Types of tool functions participants suggested to assist sustainable design efforts. The size of the circle corresponds to the number of times this type of function was mentioned, while the axis indicate how often this type of function was mentioned in response to tooling to increase control (horizontal x-axis) and impact (vertical y-axis).

4.4.1 Improving Control To improve control, participants want tools that can improve information transparency and support decision-making. The participants highlight a lack of transparency of manufacturing and materials suppliers (see 4.3.1). This can be addressed with tools that provide designers with information and search options about materials and material properties, such as through the development and expansion of libraries, databases, and guides containing information about material properties and their impact on sustainability. For example, P12 suggested *"a list of materials that we can choose from that are more easily recovered and recycled, we'd be able to pick one knowing there's a chance it could be recycled. Currently, with so little cost-effective recycling going on, it's hard to know what is realistically recyclable"*, while P18 highlighted that *"Lists of hazardous materials and regulations can be very helpful"*.

Participants also indicated that they lacked visibility into the impact of their and others decisions on sustainability. An example of what such information transparency might look like is provided by P22, who imagined *"A tool that could show me the greenhouse-gas footprint of my design through the entirety of the supply chain - from actually making the raw resins, plastic molding, metal stamping, etc. through to the shipping of the product from original factory to distribution centre(s) to end customers. Seeing that greenhouse-gas map along the value-creation journey would be fascinating and useful"*.

Unfortunately, simply providing information is not enough. Tools serve to support design teams to make better decisions when selecting processes and suppliers: *"For me it will be worthwhile to learn more about the energy / water usage, and greenhouse emission tied to each of these manufacturing processes* *so that I could make more informed design decisions with our team"* (P16). Additionally, participants want those tools to be integrated into their existing tools and processes: *"We make heavy use of ECO material adviser (which is still available for Inventor 2020) to determine the lesser of multiple evils when picking our materials for a new product. But we would like to see this module expanded because our clients are often governmental or semi governmental utility companies. These are required by law to have material passports for all their new assets"* (P6).

4.4.2 Understanding Impact

To help understand impact, designers want tools that can predict results. The participants were uncertain about how much impact strategies have on sustainability, and which strategies are more impactful than others. Potential solutions for this problem include tools that enable designers to compare options and evaluate the impact of their decisions and processes on other factors, such as on product cost and sustainability. For example, P7 suggested that *"It would be great to have a tool that allows evaluating design decisions not only on product performance and cost metrics, but also sustainability. Think of a tool that allows evaluating the "environmental cost" of different design alternatives depending on the materials or the components used"*. P12 expanded on that idea by saying that *"If I need to pick a material to use for a product, it's difficult to know the true cost of each choice. What if I could use a tool that allowed me to pick material, location of source, location of manufacturing, etc, then it gives me a life cycle analysis of that material. Same for every other decision (manufacturing method, location of manufacture, etc)"*.

Moreover, participants wanted to be able to simulate their products' performance, such as over time or under particular situations. Thus, tools are needed that can simulate how multiple options will impact the products performance or impact on sustainability and other factors such as cost: *"We use a whole range of test methods to simulate rapid aging of products. High temperature sequence testing, salt water high humidity test bath and high pressure bunker external/internal leakage test (100bar)"*(P6).

4.4.3 Tool Adoption

To increase the business case for sustainability, designers want tools to share knowledge and discover user needs. The participants lack insight into which sustainable design practices could best match their situation. Therefore, tools are needed to support designers' ability to share knowledge with fellow practitioners, for example through *"more published technical white papers and documents that show list of sustainable alternative materials and their mechanical properties"* (P9). By extension, P24 highlighted the importance of industry wide changes: *"Component compatibility would be improved if the industry held a larger standardized catalogue of some of the unique components that had to be custom-designed in this product effort"*.

Participants also desire better alignment between sustainability and user needs, but lack reliable channels through which to communicate with users and thus worried about user backlash. Tools that address this problem should support designers with *"tools to educate clients why sustainability matters to us and why it should matter to them"* (P29). One approach is through the development and nurturing of communities of interest, for example around repairability: *"Supporting easy repair is very impactful because it saves customers more money and empowers them to learn technical skills and gives them confidence to fix other things that they own. iFixit is the most prominent tool that has had a huge impact here: I'm a huge fan of them for this reason"* (P15).

Designers want tools that appeal to both low and high control situations, as long as they are highly impactful. In the interviews, we asked participants in which area (high or low control and impact) they would most like to see tools. Almost all interview participants indicated a desire for high impact tools. For example, P10 would want to *"put everything in stuff we would have high impact and that we have more control over"* because that combination represents "low hanging fruit" opportunities. However, high impact and low control tools are also valuable because *"More control equals more impact. So spend more money in high impact and low control for a tool that can give me the opportunity to have more control"* (P5). Another participant also cautioned against the gut reaction to only develop high control tools: *"High control does not necessarily always translate to positive impact. Let's consider the method metaphor of over time. Say you have a river which periodically floods the valley. So you decide to build a dam to prevent the floods. But then, once every 100 years, comes a huge storm which breaks the dam so now the whole area is flooded instead of just the valley! So you have implemented a high control strategy, but in the end, you actually made things worse because instead of going with the smaller impact floods, you actually got one big one!"* (P7).

5 Discussion

In the pursuit of a more sustainable world, designers sit at the heart of innovation, implementation and impact. While there are larger systemic issues that need to be addressed to improve sustainability, designers also have considerable impact on the final design of their products, and substantial work has been done to make more sustainable product design methods and tools.

In this study, we explored the opportunity areas and tool functions that designers care about and how those map to their perception of control and impact. To summarize our findings, firstly designers are most interested in tools for opportunity areas that have a high impact on sustainability. For example, tools that help predict design outcomes during product design. Secondly, designers want tools that improve access and transparency of information in areas that are further from their direct control, like manufacturing. More information can help designers gain more control and improve their understanding of impact. Lastly, tools that help share knowledge with other designers and user communities, and tools that support the discovery of user needs can help align business models closer to sustainability. As more customers prioritize sustainable products, adopting business models that respond to this market change will have a positive ripple effect that will contribute to the virtuous cycle of sustainable designs. Generally speaking, the designers argued that they would like to design more sustainable products, but that they do not have the time, energy, or resources to do the research required and would therefore rather make a selection from a list of alternatives that best fits their use case.

Design practice is grounded in the socio-ecological and economic realities of the systems that societies currently operate in. Specifically, since so many of our incentive structures equate growth and abundance with economic success, designers and customers have internalized these messages. These broad structures operate at levels much bigger than any one designer alone can address, and efforts to re-prioritize sustainability often are in direct contradiction to the very structures have been put in place to prioritize growth, market choice, and freedom. Several participants elaborated on this very contradiction that they often encounter when incorporating sustainability in their design. For example, Industrial Design prioritizes on bringing the most appealing products with compact forms. If sustainability is not a priority at the beginning and throughout the design process, then compact forms often lead to less room for standardized components that may be bigger and harder to fit than customized ones; and consequently less room to incorporate repairability and upgradability. Engineering often sets ambitious goals on cost and performance. If sustainability is not what engineers start with as a requirement that is to be prioritized, then it is often traded off during the design process. Designers and engineers are pressed by time to deliver products with latest technology and the most appealing design. This is driven by consumers' willingness to pay for products that have the latest technology, are the most powerful, or the cheapest, rather than the most sustainable.

Shifting these design paradigms is not an easy task; it requires that we redefine regulations and reshape consumers' priorities when it comes to sustainability. In the interim, designers and design researchers must acknowledge these paradigms we operate in, work to develop tools and methods that effectively interrogate and push the boundaries of how design is done, and actively share knowledge across these boundaries for sustainability, a big problem that we can only solve together.

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