Introducing the Sustainable Prototyping Life Cycle for Digital Fabrication to Designers

Eldy S. Lazaro Vasquez
Department of Design
University of California, Davis
Davis, USA
eslazaro@ucdavis.edu

Hao-Chuan Wang
Dept. of Computer Science
University of California, Davis
Davis, USA
hciwang@ucdavis.edu

Katia Vega
Department of Design
University of California, Davis
Davis, USA
kvega@ucdavis.edu

ABSTRACT
This paper introduces the *Sustainable Prototyping Life Cycle for Digital Fabrication*, an adaptation from the Life Cycle Assessment method that presents the environmental impact of digital fabrication in every phase of prototyping. The cycle has four phases: raw materials acquisition, manufacturing and distribution, use, and end of life. It presents designers as manufacturers of their own materials for digital fabrication, and bio-based materials are used as an alternative and sustainable prototyping material. We interviewed ten experts in digital fabrication and introduced the use of bio-based materials such as mycelium-composite for prototyping with digital fabrication.Using experts’ reflections, we conducted a workshop about the environmental impact of prototyping with 22 design students. We reported their decisions on materials used for prototyping and their perception of using mycelium-composite within the Sustainable Prototyping Life Cycle. Our aim is to increase environmental awareness in prototyping and highlight the importance of designers’ decision-making through the cycle.

Author Keywords
Sustainable Making; Prototyping; LCA; Digital Fabrication; Bio-based Materials; Mycelium-composite; Sustainability

CCS Concepts
•**Human-centered computing** → **User studies;** *Interface design prototyping;*

INTRODUCTION
There is concern regarding how sustainable and environmentally friendly the practice of digital fabrication is as well as the materials used for prototyping [17]. This topic has also been a concern in the HCI community. Muller and Baudisch’s monograph, for instance, states that sustainability is one of the challenges that research in personal fabrication should address for long term success [4]. Prototyping with digital fabrication includes the use of materials and machines. There are methods and tools to assess quantitatively or qualitatively the environmental impact of design, in terms of CO_2 emissions, energy consumption, land depletion, and waste. For instance, the Life Cycle Assessment (LCA) is a cradle-to-grave method to evaluate potential environmental impacts of not only materials but products, processes, or services [3], [23]. We made a variation in the LCA method to design a Sustainable Prototyping Life Cycle for Digital Fabrication where designers become manufacturers of their own prototyping material with the aim to make the practice of prototyping more sustainable. The cycle has four phases: the acquisition of raw materials, the processes used for manufacturing the material and distribute them to the designers’ labs, the use phase which includes the digital fabrication techniques used for making the prototypes, and finally the end of life phase which is basically the way we dispose our prototypes when we do not use them anymore.

We grew and used mycelium-composite, the roots of fungi, as a prototyping material because it has low impact and presents suitable properties for prototyping such as heat resistance, thermal resistance, lightweight, shapeable and hydrophobic [2]. The main contributions on this paper include:

1) The adaptation of the LCA for digital fabrication. We called it *Sustainable Prototyping Life Cycle for Digital Fabrication*. It presents the environmental impact in every phase of prototyping with digital fabrication. We implemented the cycle with bio-based materials to envision an alternative and sustainable material.

2) Online survey with 60 users of digital fabrication techniques, qualitative interviews to 10 experts, and a workshop with 22 design students to investigate how environmental impacts are understood and considered in prototyping practices in different design groups. Reflections and the potential of using bio-based materials for prototyping.

3) Implications for design practitioners, researchers, and educators to address environmental sustainability in their lab or when teaching this topic in a classroom.

The paper contains *Related Work* that outlines how DIS community has addressed environmental sustainability and the use of bio-based materials for prototyping in design, *Sustainable Prototyping Life Cycle* that presents the notion and process of sustainable prototyping, *The Current Work* in which we present observations and findings obtained from studying how

DIS ’20, July 6–10, 2020, Eindhoven, Netherlands.

ACM ISBN 978-1-4503-6974-9/20/07 ...$15.00.
https://doi.org/10.1145/3357236.3395510

designers perceived and used bio-based materials to prototype. We then discuss the findings and conclude this paper.

RELATED WORK

Sustainability in the field of Human Computer Interaction (SHCI) has been addressed from different research approaches such as Sustainable Interaction Design (SID), which promotes renewal and reuse of objects or systems [5], or Sustainability in Design [21] which considers the issues related to energy footprint, reduction of waste, reuse, and recycling to design products [26].

For addressing sustainability in the making process, Roedl and Bardwell highlighted the makers' role as agents of positive social change due to their ability to repair and reuse artifacts [27]. Researchers in the DIS community have also had an approach to the topic of sustainable making [27]. Some investigations rely into reducing waste [6], [7], designing with reused materials, found and broken objects [13], or the practice of reusing electronics creatively [16]. In our project, we take sustainable making beyond a reusable process (end of life phase), but we pay attention to the whole prototyping cycle that includes the use of low impact materials, techniques and machines to design or prototype more sustainably.

Materials play an important role in digital fabrication, because they have the ability to influence ways of making. Designing for material recuperation [31], or using materials as speculative tools [32], [11], [20] shows innovation of materials in the design community. Alternative sustainable 3D printing materials have been also researched [22], [8], as well as a study that can improve the environmental implications of 3D printing with novel materials [9]. If materials have started changing the way we design, they can also be agents of positive environmental impact while transitioning to a circular design practice.

An emergent sub-field of design is called bio design [30]. The use of bio-based materials in this sub-field such as bioplastics, bacterial cellulose or algae have been adopted for many designers across the globe and within many design fields. Researchers and designers have found a big opportunity in bio-based materials, especially the ones created with living organisms such as mycelium, to show novel possibilities in design to reduce designers' environmental impact[15].

For instance, Suzanne Lee pioneered the use of bacterial cellulose to make clothing [19], mycelium-skin has been used to make more sustainable wearables [29], mycelium-composite was used to embed electronics [28] or to make low-fidelity 3D models [33], and bio-plastics have been used to make garments and accessories such as bags. Between the most common bio-based materials, mycelium is potentially suitable for replacing MDF, cardboard, or mat board due to its heat resistance, thermal resistance, and the properties of being lightweight, shapeable and hydrophobic [14].

Looking into the end of life of common prototyping materials (Tab.1), bio-based materials such as mycelium-composite takes up to 90 days to degrade in natural conditions, unlike MDF that takes 13 years to degrade in the landfill because it is not a recyclable material. A few types of acrylic are recyclable, however the ones that are not will take up to 400 years to degrade in the landfill. Cardboard which is a recyclable material can take up to 2 years to degrade if it ends up in the landfill. Digital fabrication techniques used for laser cutting common materials such as MDF and acrylic emit toxic fumes when laser cutting because of the composition in the material, unlike bio-based materials that do not have any toxic additives or resins on the material's composition.

	Degradation Time	Recycle	Compost	Danger (laser cutting)	Common Thickness	Application
Biomaterial (mycelium)	90 days	No	Yes	-Burn -Catch fire	1-7.5mm	Craft, decorative
MDF (Fiberboard)	13 years	No	No	-Smoke -High formaldehyde -Fumes	3-10mm	Technical, decorative
Acrylic	400 years	Yes	No	-Melting -Fire hazardous -Fumes	2-5mm	Technical, decorative
Cardboard	2 years	Yes	Yes	-Burn -Catch fire	3-6mm	Craft, decorative
Fabrics (nylon, polyester)*	30-200 years	Yes	No	-Burn -Catch fire	up to 1mm	Decorative

Table 1: End of Life of common prototyping materials and mycelium-composite [2], [10], [25].

SUSTAINABLE PROTOTYPING LIFE CYCLE

We present a sustainable prototyping life cycle (Fig.1) to address the environmental impact of prototyping with digital fabrication which includes four phases: Raw materials acquisition (materials needed to make a bio-based material), Manufacture and distribution (make the material adequate for digital fabrication and deliver it to the lab), Use (decision-making of materials and digital fabrication techniques to use for prototyping), End of Life (reuse, recycling and disposal of prototyping materials).

The cycle's phases were adapted from the traditional Life Cycle Analysis method which examines the environmental impacts of a product by considering the major stages of a product's life [3]. For the purpose of this study, we translated those concepts into the phases that are involved in a prototyping life cycle.

Raw Materials Acquisition

This stage includes material harvesting and transportation to manufacturing sites. In our cycle, this phase includes the raw materials we need to make our prototyping material, or in case we buy it, we won't have a direct participation in this phase but the emissions generated in this phase will still be part of the environmental impact of prototyping. For instance, to make kombucha fabric, the raw materials would be the symbiotic colony of bacteria and yeast (SCOBY), black tea, water and granulated sugar; to make mycelium-composite (mycoboards), the raw materials would be straw, hemp or flax inoculated with mycelium, flour, and water (Fig.2); to make one type of bio-plastic, the raw materials would be glycerine, cornstarch, white vinegar and distilled water.

Mycelium is a fast-growing vegetative part of a fungus which is a safe, inert, renewable, natural and green material which grows in a mass of branched fibers, attaching to its own environment [1]. Mycelium based materials have a wide variety

Figure 1. Sustainable Prototyping Life Cycle and the emissions released in each phase.

Figure 2. Raw materials to make mycelium-composite: a. Flax, b. hemp, c. flour and water

of applications and they have the advantage of low cost of their raw materials (flax, hemp, coffee grounds, aspen, or any other fibrous substrate). It has natural heat resistant, thermal resistant, lightweight, degree of strength, shapeable and hydrophobic properties [14], which makes it adequate to embed electronics [28] or prototyping.

Manufacturing and Distribution

This stage includes product manufacturing and assembly, packaging, and transportation to final distribution. In our cycle, this phase includes the processes necessary to make our prototyping material inert and in a shape that we can digital fabricate later (laser cut, 3D print or CNC machine). Energy, fuel consumption and emissions are considered part of the environmental impact of prototyping in this phase, even if we do not have an active participation in the manufacturing process. For example, to make kombucha fabric, the manufacturing phase would go from the growing to the harvesting of our prototyping material. It will include the containers to grow the bacteria culture until we get the desired thickness in our wet mat (about 3 weeks), the washing process with cold soapy water, the dying process if desired, and finally the drying process that can be outside in the sun or in a dehydrator; to make mycelium-composite (mycoboards), this phase will include the molds (cooking sheets) in which we will grow the material for 6 days, the drying process that can be under the sun or in an oven, and the compression process using a hydraulic compressor to get even mycoboards and in the desired thickness to laser cut later (Fig.3); to make bio-plastic, this phase would include the cooking process in a stove, the drying process in cooking sheets or mats and under the sun or using a dehydrator.

Regarding distribution in this phase, it is usually related to the CO_2 emissions generated by the type of transportation used to deliver the materials to the final distributor. In our cycle, we can avoid having that environmental impact if we grow or make our materials in our own lab or nearby facilities.

Growing mycelium (Fig.2) in any substrate such as flax or hemp takes about 12 to 15 days in regular conditions which are at room temperature and humidity. The growing process can be divided in three: the activation, the molding and the compression process. For the first 2 phases, the mycelium-composite should grow in a dark area before drying the mycoboards in the oven or under the sun. For the last phase, a manual hydraulic press machine is necessary to perform the material compression.

Activation process. We used an already commercialized 'Grow-It-Yourself' Mushroom Material [12] which contains the mycelium in a dormant status combined with hemp (substrate) where the mycelium is going to grow through. To start the activation process, we added flour and water inside the bag and we stored it in a dark area for about 4-6 days at room temperature (27°C or 80°F). After that time, the substrate will turn into a white color that indicates the mycelium colonization was successful(Fig.3b).

Molding process. After the activation process, the mycelium-composite material is ready to use. We break the material down and it is transferred to a mold and it starts growing in that shape (Fig.3a). For this study, we transferred the material to flat rectangular molds with different thicknesses from 5mm to 9mm. We covered the molds with a bioplastic film and made some cuts in the surface to enable the mycelium to breath. After, we put the molds in a dark area for about 4-6 days until it becomes white again (Fig.3b). Finally, we took the grown mycoboards out of their molds and put them into the oven (80°C or 194°F) to stop the growing life cycle or they can also be dried under the sun for about 2 days. This step is basically to kill the mycelium life cycle and to obtain mycoboards. After this phase, the mycoboards are ready for the compression process.

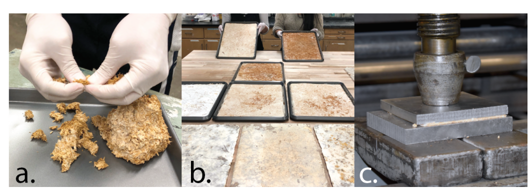

Figure 3. Manufacturing process in the lab to make mycelium-composite (mycoboards): a. Breaking down the material, b. Growing the material in molds, c. Compressing the material

Compression process. We used a manual hydraulic press machine to perform the compression tests in the 5mm and 9mm. mycoboards. We went through this step because we wanted to simulate a regular material for prototyping such as cardboard or matboard which are not only thin materials but even. We applied different pressures per inch (psi) on the mycoboards to test degrees of strength on them (Fig.3c). We were able to reduce the mycoboards' thicknesses to 2, 3, 4, 5, 6, and 7.5mm. The aim of this process was to get a denser, flatter and smoother material for laser cutting, and ultimately we got mycoboards with most common thicknesses used for prototyping.

Use

This stage includes energy and emissions during normal product life, required maintenance, and product reuse (refurbishing, material reuse). In our cycle, this phase includes the decision-making of materials and digital fabrication techniques used in our prototyping process. These decisions will vary from low to high fidelity prototyping. For instance, deciding between 5 hours 3D print versus 30 minutes 3D molding mycelium-composite for low fidelity prototyping, or deciding between MDF and acrylic for high fidelity prototyping knowing the end of life of both materials. When using bio-based materials, this phase encourages designers to decide in between a material that takes 3 weeks to grow versus a material that takes 1 week to grow and to base their decision on the resources needed to grow each material in contrast with its physical properties.

Digital fabrication: laser cutting mycelium-composite
Laser cutting is one of the most used digital fabrication techniques. We made test cards to laser cut 2, 3, 4, 5, 6, and 7.5mm thickness mycoboards. We laser cut every mycoboard to know if this technique works as good as it works in cardboard, matboard, acrylic and plywood, which are the most common materials used for prototyping based on a survey we performed for the purpose of this study. We used a PLS6.150D Universal Laser System machine to make all of our tests and the results are described lines bellow (Fig.4).

Figure 4. Mycoboard test cards laser cut in different thicknesses.

Prototyping: Product Design.
This category includes enclosures, 3D scaled models, 2D designs, so on and so forth. To explore the viability of using the material (mycoboards) in prototyping the designs of products, we made 4 different common prototypes based on the responses we collected from a survey probing the current practitioners of digital fabrication regarding what kinds of prototypes they make the most. Details about how we did the survey are to be presented in the next section of the paper.

The first prototype we made was a lamp shade. We designed a 3D shade for a desk standing lamp and we laser cut the pieces in a 5mm. mycoboard. The technique we used for assembling the lamp shade was press fit and we kept a 0.1mm. tolerance for the joints, the same tolerance which is used for cardboard material when laser cut (Fig.5a). The second prototype was a SD card holder. We used 2mm. mycoboard and only 3 layers of it were necessary to make it. The pieces were stacked together using crafting glue which was made from a cornstarch glue recipe. It worked pretty well and the 2D design of the prototype was made in Illustrator following a real SD card holder measurement (Fig.5b). The third prototype was a candle holder and we applied the same technique applied for the previous one. We got the 3D model from an open source website called Thingiverse and we edited the file in Slicer Fusion 360 for obtaining 2D model pieces to laser cut. We followed the parameters tested in the previous stage of the cycle and laser cut all the necessary pieces in 4mm. mycoboard (Fig.5c).The last prototype in this category was a business card. We used engraving, marking and laser cutting for making it. We used 1mm. mycoboard to cut this prototype which was designed in Illustrator (Fig.5d).

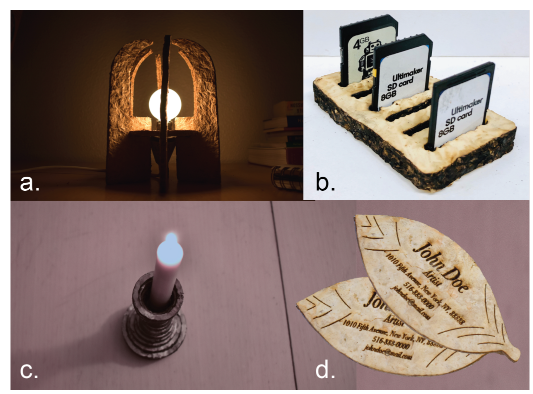

Figure 5. Product design prototypes using mycoboards.

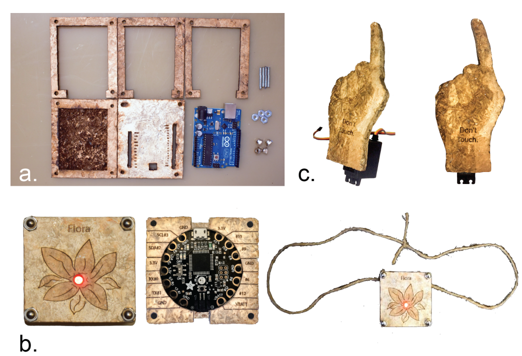

Figure 6. Interactive Objects prototypes using mycoboards.

Prototyping: Interactive Objects.
This category includes chassis for microcontrollers, DC motors, servos and so on. We made 3 different common prototypes based on the surveys participants answers about the kind of prototypes they make the most. We designed enclosures with laser cutting for both microcontrollers,

arduino UNO and flora. We used a 3mm mycoboard to make them. The prototypes’ pieces can be assembled and disassembled easily. The design includes the use of screws on the corners of the enclosure, so the microcontrollers can be removed from it whenever needed. The design also helps with the re usability of the electronics, and the enclosure can be disposed of in a compost bin after it becomes an unused prototype (Fig.6a,b). The other prototype was an interactive hand sign which has a servo motor embedded on it from the back side of the piece. We used a 4mm. mycoboard that we engraved and laser cut to make this prototype. The interactive hand is activated by a switch every time a person gets closer to it (Fig.6c).

Figure 7. Mycoboard end of life: a. compost bin, b. natural conditions, c. up to 90 days to degrade.

End of Life

This stage includes waste management and end of life of products: recycling, landfills, liquid waste, gas emissions, etc. In our cycle, this phase includes the reuse and disposal of prototyping materials properly. For instance, making sure that PLA is being disposed of in a separate trash bin that later is going to be taken to a specific facility for recycling, or that bio-based materials are being disposed of in a compost bin. Same with cardboard and matboard, which are recyclable materials and they should be disposed of in a recycling trash bin. Regarding waste management, our cycle encourages to have a better disposal system in our labs to reduce the environmental impact of prototyping materials, because the main issue with waste becomes when it is disposed of improperly.

Waste management: leftovers, mistakes, unused prototypes
Based on the survey we performed as part of this study, it was inferred that participants have a hard time deciding about disposing or not the materials used in the prototyping process. They expressed their concern about the amount of leftovers they keep and that they think they will use in future projects. However, they end up storing disposable material such as leftovers and unused prototypes for more than a year. We addressed this concern in this part of the prototyping cycle by replacing common prototyping materials such as MDF, acrylic, plywood for a bio-based material such as mycoboard, which is 100% compostable. In consequence, leftovers, mistake pieces generated by the multiple iterations made in the design process, and unused prototypes because designers moved fast from one project to another, can be disposed of anytime during the prototyping process creating peace of mind in the participants about their waste.

Composting: up to 90 days.
Based on the survey, almost 65% of the participants claimed lack of a recycling process for their waste material in their labs. Common prototyping materials such as PLA, acrylic, or MDF can remain in the landfill for hundreds of years as any other piece of plastic if they are not disposed of under the right conditions [18]. Mycoboard is a compostable material that can degrade in up to 90 days as any other organic waste. It can be disposed of in a regular compost waste bin or even in natural conditions. This bio-based material can be a great alternative to participants who lack the facilities to recycle or dispose their waste properly.

THE CURRENT WORK: PUTTING THE CYCLE IN ACTION

For the purpose of this work, we mainly focused on the last two phases of the cycle in which designers commonly have an active participation when prototyping: Use and End of Life. We followed various steps to design the study. First, we conducted an online survey to advanced digital fabrication users to identify current prototyping cycle and waste management processes. We then designed prototypes with mycoboards based on what people recommended in this survey as introduced in the previous section. Second, we interviewed design experts in digital fabrication to acknowledge their reflection about the use of a bio-based material for digital fabrication. Furthermore, we collected their reflections about best ways in which novel bio-based materials can be introduced to novice design students in a classroom setup to foster their thinking about materials decision-making. Third, we conducted a sustainable-focused workshop with novice designers using the Sustainable Prototyping Life Cycle to understand their reasoning and decision-making regarding materials use along their design process.

1. Online Survey. A sample of 60 advanced users in digital fabrication techniques recruited online from North America (21%), South America (38%), Europe (21%), Asia (11%), Africa and Australia (9%) participated in the survey. The results of the survey were used to decide the introduction of the mycelium-composite material, digital fabrication techniques and the type of prototypes we were going to showcase in the interview to experts.

Open ended questions were used to understand participants’ perception of waste in their labs. The most digital fabrication techniques used were laser cutting and 3D printing, 37.2% of the participants rated laser cutting as the technique that generates the most amount of waste in the prototyping process, followed by CNC machining with 33.7%, 3D printing with 22.1%, and electronics and programming with 4.7% and 2.3% respectively. About materials, 32.6% of the participants mentioned that MDF is the most used material for laser cutting, followed by acrylic, cardboard, fabrics such as nylon and polyester, and 14.7% of the participants said that PLA is the most used material for 3D printing.

Participants categorized the type of projects they prototype for in their labs or maker spaces. Product designs were the kind of projects most ranked with 54.8%, followed by interactive objects with 24.2%, fashion with 11.3% and 9.7% in between architectural and educational projects. Participants reported storing unused prototypes in their labs which included 52.5% scaled models, 39% enclosures, and 8.5% others. Finally, reasons for keeping unused prototypes in their labs include breakage, one-use purpose, and moving on to a new project. More than 90 % of the participants claimed they have unused prototypes in their labs. The survey also shows that 47.5% of the participants have had their unused or broken prototypes for more than a year, 27.5% for 6 months to a year, and only 15% do not keep unused or broken prototypes in their labs. Additionally, 61% of participants did not consider unused prototypes as waste.

In the last part of the survey, 64.3% of participants said they do not follow any recycling waste process and they dispose their waste in a standard landfill trash, 23.2% said they recycle materials such as cardboard or paper, and only 12.5% of them use materials scraps for reuse in future projects. Participants expressed their concern about the large amount of material they use from the initial to the final prototype. They keep many unused prototypes because they are old, broken or they use them to showcase in their labs. Surprisingly, the time they keep leftovers, and unused prototypes in their labs are mainly for more than a year and that is because 61% of the participant do not consider these prototypes as waste.

2. Design Experts Interview. We interviewed 10 design experts in digital fabrication and we collected their reflection about mycelium-composite used for prototyping, best ways in which bio-based materials can be introduced to novice design students in digital fabrication in a classroom setup to foster thinking about materials decision-making. The interviewees were experts in areas of product design, arts and education with more than 10 years of experience in their field, and their professional practice was related to design. The participation was voluntary, video and audio recorded and the interview took 45-60 minutes to complete.

A. Study introduction and qualification questionnaire.
This part of the interview helped us to know interviewees skills set about digital fabrication techniques such as laser cutting, 3D Printing, CNC machining, electronics and programming. We also asked for information about the different materials they use along their prototyping process, their awareness about ecological materials' applications in any field, and their disposal waste practice prototyping.

B. Mycelium-composite samples' observation session.
Interviewees were invited to a 20-minute observation session of mycelium-composite samples. We started explaining what ecological materials are and how they are used to introduce mycelium-composite as a prototyping material afterwards. We explained the life cycle of this novel material, from the growing process to the compostability of it. Furthermore, we described mycelium-composite properties which make it more suitable for replacing fiberboard (MDF), acrylic, or plywood due to its heat resistance, thermal resistance, lightweight, shapeable, hydrophobic, and degree of strength properties [14].

We showed case prototypes (Fig.4, Fig.5, Fig.6) that were made as a proof of concept that this material can be applied in interactive objects, product design, and wearable technology prototypes. All the samples were made using laser cutting because that is one of the most common digital fabrication techniques used for prototyping. We also prepared some mycelium-composite test cards for laser cutting and engraving. They came in different thicknesses from 2mm. to 7.5mm.

C. Interview about the observation session.
The interviewees had a 20-minute recorded interview to discuss how they could envision mycelium-composite use in their fields. The purpose of the questions made in this section was to identify the interviewees' perception on mycelium-composite material compared to the ones they commonly use, the applications and processes in prototyping where this material could or could not be successfully used for, the common mistakes they make when prototyping, and finally a question about the possibility of replacement the current materials they have in their studio/lab with an ecological one.

D. Summary questionnaire.
Upon completion of the interview about the observation session, interviewees were asked to complete a 15-minute summary survey which included open-ended questions to envision the use of ecological materials in prototyping. Our main goal in this part of the interview was to know more about experts' awareness on sustainability in their practice. We also asked interviewees for alternative ideas to address waste issues in prototyping, the measurements they have adopted along the years to reduce waste and to become more environmentally friendly in their studio/lab, and finally, we asked them for effective ways they think a new ecological material could be presented to novice users of digital fabrication. We plan to use all the gathered information to design a workshop for novice design students to introduce the use of an ecological material, mycelium-composite, successfully in a classroom setup.

Findings

All the 10 experts work with laser cutters and 3D printers, 6 of them work with CNC machining, and 4 of them also work with electronics and programming. The experts fields are 4 in education, 3 in product design, and 3 in arts.

The experts gave descriptions about their prototyping process, specific materials they use in every prototyping iteration and the materials their students or community usually use for the same purpose. All the interviewees agreed that the prototyping process goes from low fidelity, medium to high fidelity prototypes and the materials they use follow the same process. Experts workflow starts prototyping with paper until they get the shape, size and scale desired, then they change the material to a stronger one that it's mostly cardboard, plywood or foam cord or fabric in case of art projects, and they end up using a better aesthetic material for the high fidelity prototype such as acrylic. Explaining the prototyping process, one of the experts mentioned:

E1: "I also use plastics and papers to get dimensions right as a first step. I use paper to get dimensions, to figure out the sizes of my model".

We asked for the period of time interviewees keep the prototypes in their labs or studios, and they said they dispose their iterations at the end of the day or the week if it's a bigger project. The only prototype they keep to showcase is mainly the last one. Expert 1 (E1), who teaches a prototyping class, said that his students like using foam-cord as a prototyping material for making their scaled models from the first iteration and they use this material in every iteration. The interviewee's guess was that his students might be using foam cord because that was the only material that was introduced to them as a prototyping material since they started school. He expressed his admiration by saying:

E1: "My students use foam cord mostly in their first prototypes, and I do not know why! There's a tremendous amount of waste. The prototypes won't last more than 1 week in the lab. We don't keep them longer than that".

Part of the interview was about waste and recycling processes. 70% of the experts claimed that they do not have a recycling process in their labs or facilities where they work. On the other hand, E5 highlighted that a recycling and compost system in the maker space is required:

E5: "Our university is under a zero waste project and the only materials students are allowed to work with here are plywood (90%) and acrylic (10%). Our plywood is 100% compostable".

Most of our interviewees expressed that the only material they recycle are paper and cardboard. E1 for instance, label the trash bins to make sure people in their lab are disposing materials in the right trash bin.

E1: "I try to very clearly label all of the bins and make sure I have recycling in all the spaces. If people are not recycling properly, then I will let them know. Making sure the trash is in the right bin".

After the observation session and introduction to mycelium-composite material and different application in design, we asked the interviewees for current materials they have in their lab or studio that they would like to replace with an alternative, 100% of them claimed that acrylic and plywood would be the the ones they would like to replace because they are not even recyclable and end up in the landfill.

E10: "I would replace acrylic. It is very useful, but it's expensive and it's not sustainable".

E5: "In a rapid prototyping setting. It's important how this fits into a larger conversation of ethics, that's a good place for it, not just to say here it is an ecological material, a conversation about what are we designing, why we are designing it? Are we thinking about the planet while we're doing it? Are we thinking about the impact this object is going to have in the world? Where are you going to get the materials from and what is going to happen with it when its life is over? That's something that designers should be thinking about, willing in the school and then the entire time they will design. Having it by itself it would not have a major impact as being part of a larger conversation".

At the end of the interview we asked experts for their concerns about sustainability and best ways to present an alternative material (bio-based material) to novice designers in a classroom set up. Some of the comments and suggestions we got from them were:

E3: "My concern is going back to the teaching as how do you teach students this (sustainability) and how do we incorporate it as a field, With the students, how you go from something 'this is important', but to get them in a systematic way to study it a little bit more before they go out and work for a company, How can we help students start to think about it as a problem but be aware of possible solutions and how they can be a part of the solutions".

E6: "We supply students materials and they take advantage of them. So, I think that's great to do as long as you actually supply them. Whatever you supply them with that's the choice they are gonna make most likely".

E9: "I like it (one of the mycelium-composite test cards), this is your info, your life cycle analysis. This is what the material is and you can pass it around and they (students) can touch it, and they see it, and they can have a little lesson that is on here, the life cycle analysis of what this is, and they can touch it and they can hold it... I think having info cards is a good idea. If you give this as a take away, they can take it home and then put it in your garden, put it in your houseplant and see how it decomposes".

Figure 8. Workshop with novice designers

3. Workshop with Novice Designers. The workshop protocol consisted of three parts, (A) intro to prototyping, environmental impact of materials, and digital fabrication, and (B) Mycelium-composite as a prototyping material, prototyping exercise using laser cutting, mold making with mycelium-composite, and (C) a survey and an open discussion. The workshop was divided into three sessions based on experts' suggestions.

We conducted this workshop with 22 novice design students. They were 2nd and 3rd year undergrads and they didn't receive any compensation for their participation in this workshop. The participants didn't have previous experience with digital fabrication techniques (laser cutting or 3D printing). The workshop took 2.5 hours to complete and it was divided in 30 min. intro to prototyping and materials impact, and 1.5 hours of hands on activity.

The main purpose of this workshop was to understand participants' reflection about the environmental impact of materials. The workshop followed experts' suggestions and it was divided in 3 sessions that happened 2 times. During the 1st session, participants were asked to design an electronic component enclosure using a 2D program such as Adobe illustrator. They were allowed to iterate up to 3 times and pick their preferred material to laser cut in between matboard, acrylic, plywood and mycelium-composite (Fig.8).

Survey
We conducted 2 surveys and 1 open discussion in the workshop. The first one was at the end of the first day of the workshop and the second one was 2 days after the first workshop activity. We decided to do that because we wanted to understand students' reflection about materials' impact before and after interacting for a while with the material. We used open-ended questions in both surveys to obtain as much information as possible from students about their materials' decision-making.

We collected information about participants' decision making about the materials they chose for their first, second, third and final iteration for the laser cutting exercise. Participants had 2 days to complete this exercise which was a workshop assignment (Fig.9).

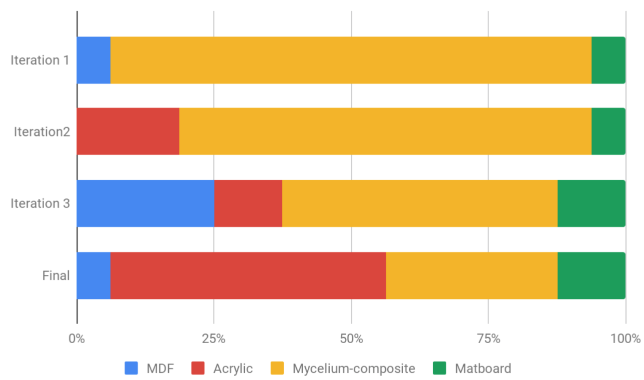

Figure 9. Materials' decision-making of participants in their prototyping process (Iterations VS Materials)

In the first iteration of their prototype, 87.5% of the participants chose mycelium composite as a prototyping material, in the second iteration this number decreased to 75%, and acrylic appeared as a second preferred material of 18.8% of the participants. In the third iteration, only 50% of the participants chose mycelium as a prototyping material, 25% chose MDF and the other 25% of the participants chose between acrylic and matboard as their preferred prototyping material. For their final iteration, the number of participants who chose mycelium-composite to laser cut their electronic enclosure was 31.3% and 50% chose acrylic followed by 12.5% who chose mat board instead.

All these numbers show that participants used mycelium composite as a prototyping material along their first stages of prototyping, however this number slows down as the participants move forward to a high fidelity prototype (Fig.10, 11). As a result, less than half of the participants see this ecological material being used as a final prototyping material, however there is still a 31.3% of participants who commented on their material decision-making. Those who continued using it were highly aware of the implications of using the material for sustainability, but with different levels of understanding of the environmental impact:

S17: "Mycelium-composite is a great test material that is biodegradable"

S22: "This material is easy to use and it is compostable"

Some participants demonstrated much deeper understanding in its impact on environments:

S7: "I kept using mycelium-composite because it have a less ecological footprint"

S12: "I chose this material because it fulfill the purpose, it has 90 days compost and it does not negatively impact the environment"

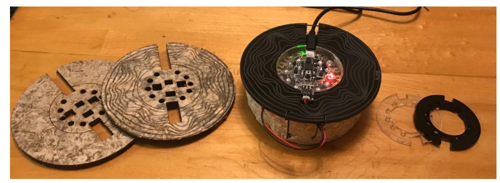

Figure 10. Left to right: iterations 1 and 2 (mycelium composite), iteration 3 (outer/black acrylic) plus iteration 5 of inner top component, iteration 3 (inner acrylic), iteration 4 (inner acrylic)

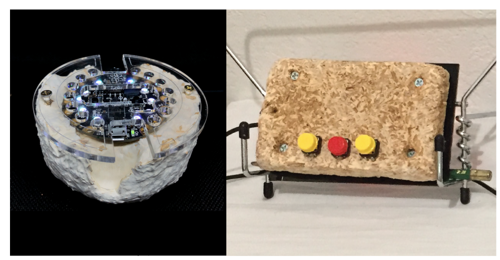

Figure 11. Novice designer's final prototype: circuit playground enclosure and mycelium speakers.

Reflections

The advantages participants found working with mycelium-composite were mostly related to its ecological properties as compostability, and freedom in making mistakes as many times as they need until reaching their desired shape and size in their design. Some students comments were:

S6: "The advantages were knowing that even if I make many mistakes and I have to laser cut again, I can put mycelium pieces in the compost bin".

S8: "Good, sustainable way to get an idea of what the final product will look like: accurate in measurement".

S11: "The advantages of using this material is that it retains its shape after it's been laser cut and it's super lightweight too!"

Some of the disadvantages the participants pointed out about mycelium-composite were related to its limitation in degree of strength, because the mycelium sheets we used in the workshop were not sturdy enough as regular materials used for prototyping such as MDF or plywood. Students highlighted this limitation as one of the main disadvantages by saying:

S3: "No challenges besides the fragility of the material, but considering that it was used for 1st iteration, it was not an issue. It was going to be thrown away anyways and I used the material mostly as a starting point".

S17: "It is a bit unsteady and it breaks sometimes"

We asked participants how they would see this material fit into their work and all of the participants envisioned this material being applied in past projects replacing the material they used for that specific project by laser cutting. Regarding 3D molding with mycelium, 95.5% of the participants agreed that they could have made past projects with mycelium by 3D molding.

S2: "I can see this material as a useful tool for prototyping as well as a good alternative to story foam, etc, as padding inside of components with a more durable outer shell."

S5: "I could definitely use this material to build architecture models. The precision of the laser cutter and the durability of the mycelium would be great for these types of projects."

S2: "I think 3D molding with mycelium can be a good alternative for preliminary drafts of 3D printed projects."

S13: "I could have created my board games by 3D molding with mycelium."

S15: "Super cool! I would do my sculpting projects with it to get that texture I can use my hardened mold."

However one of the participants argued about it by saying:

S5: "I do not believe I would want to grow my own material but it would be great if the school's design department had a center that grows it and sells this kind of eco-friendly material to students."

This last quote called our attention because it was close to what experts mentioned during the interview. Availability of material is key for introducing new materials in a classroom setting.

From the educational point of view, all participants state that they have benefited from learning about ecological materials, not only because they know that this kind of materials exist but also it made them think about their role as designers and how to make their field more sustainable.

S08: "It has made me think more about my footprint as a designer and piqued my interest about sustainable prototyping."

S12: "It opens up so many more possibilities for committing to sustainability while in the classroom."

S13: "I have benefited tremendously because I've opened my eyes to new materials that could change industrial design for the better."

Based on the survey, participants expressed their concern about the large amount of material they use from the initial to the final prototype in every project they start. The survey also shows that participants keep many unused prototypes because they are old, broken or they use them to showcase in their labs. Surprisingly, the time they keep leftovers, and unused prototypes in their labs are mainly for more than a year and that is because 61% of participants do not consider these prototypes as waste.

DISCUSSION

Our study contributes to the use and understanding of a Sustainable Prototyping Life Cycle for Digital Fabrication. The cycle aims to trigger designers looking deeper into the environmental impact of everyday design practices like prototyping. The cycle highlights all the phases involved in prototyping with digital fabrication, from raw materials acquisition to the end of life of materials used in design prototyping.

Most of the workshop participants related their environmental impact of prototyping with the end of life of the materials. Our study demonstrates that introducing a sustainable prototyping life cycle can prompt designers' decision-making of materials in their prototyping process. Participants realized that there are more phases involved that should be taken into account when assessing the environmental impact of design. Furthermore, there was a strong engagement between participants and the cycle during the hands-on experience of making their own bio-based material for prototyping.

The use of bio-based materials can be an enabler of sustainable prototyping because of its low impact in each phase of the prototyping life cycle. Here we discuss four main findings that emerged from our study: selection of low impact materials, reduction of impact during the use phase, optimisation of the end of life phase, and recommendations for an environmentally sustainable Lab.

Decision-making of low impact materials

Bio-based materials are known for their low environmental impact in the raw materials acquisition phase and end of life phase. Low impact materials are the ones made from renewable resources such as bio-based materials. They can biodegrade, photodegrade or compost in natural conditions, and/or they use clean energy to be manufactured [24].

Novice designers showed their understanding of low impact materials along the sustainable-focused workshop by using different materials in different stages of their prototyping process, from low to high fidelity. For design experts, physical properties such as degrees of strength in the prototyping material, become a main variable when making a decision about materials to use. For novice designers, they are open to incorporate bio-based materials in their prototyping process even though the material presented in this study did not have similar strength properties than MDF or acrylic.

The main challenge when choosing low impact materials is the availability of them in the market and in consequence in laboratories. Even though it is possible to grow such materials as the one we presented in this paper (mycoboards), factors such as time to grow and make the material could limit its use by experts, different from novice designers who enjoyed the experience of making as part of their learning process.

Although we reflected on novice designer's decision-making as part of the workshop findings, we realized that introducing topics such as sustainable prototyping could potentially influence their decision-making of materials in the long term which goes beyond a classroom but future professional practice where their decisions will impact millions of products when mass produced.

Impact during the Use phase

Digital fabrication techniques used for prototyping are considered part of the environmental impact of our prototypes, that is why making the right decision about which machine to use and the right parameters to do the work, is key. Experts designers showed a better understanding of the impact of this phase, they also had a major concern about the amount of energy the machines would use in a single-use prototype.

We discuss the fact that even though we come up with low impact materials for prototyping in this study, we're still using the same machines for rapid prototyping, so we will be partially reducing our environmental impact. This becomes a limitation for designers who want to design sustainable because they depend on the machines that the industry provides and which are probably not energy-efficient. However, the use of new materials can provide new opportunities for the industry to make more energy-efficient machines.

The practice of making or growing our own material also contributes to the reduction of the environmental impact of prototyping, because we are skipping the logistics and CO_2 emissions regarding distribution that are included in the environmental impact of common materials when we buy them. bio-based materials have the property of self-repair because they are made from living organisms and due to its lightweight, there is less emission in transportation when distributing the material.

The less material we use for prototyping the less impact in the environment. Deciding a low impact material to prototype with is not enough, we should also optimize the use of the materials. For instance, making our design modular to have zero waste when laser cutting, reusing scraps of materials, or arranging the pieces in the file very tight for laser cut, are some ways to create the least waste possible. Novice designers discussed this statement because they found bio-based waste positive, however having zero waste should be the ultimate goal in sustainable prototyping because we are not always prototyping with bio-based materials.

Optimization of End of life phase

Addressing environmental sustainability is a big challenge not only for experienced practitioners but also novice designers, who will likely later become practitioners, experts and design educators to pass on the knowledge and practices of prototyping to future designers. We identified that waste management and recycling practices are issues that characterize the lack of sustainable practices in laboratories. Disposing the waste in the right place and in the right conditions is a first step to make the end of life phase of prototyping materials optimal. In case of non bio-based materials, it is recommended to choose materials which are biodegradable, that can be remanufactured, recycled, composted, reused or repurposed into a different design. In case of bio-based materials, their compostable properties transform the waste in food that goes into the soil to be part of a nutrient chain for other organisms.

It is not enough to use materials because they are recyclable, it is more important to think in longer lasting products or design that embraces the principles of durability, reparability, upgradability, optimised energy and material consumption [24], and compostability.

Towards an Environmentally Sustainable Lab We encourage instructors in digital fabrication to introduce to designers the Sustainable Prototyping Life Cycle for Digital Fabrication to reflect about all the phases involved in prototyping. Decision making of materials play an important role in the cycle; however, energy use and CO_2 emissions are also present in all four phases of the cycle.

In order to have a more environmentally sustainable lab, we should be aware of the materials life cycle that we are using for prototyping. Think about that all parts of the materials life cycle generate emissions. There is a breakdown of energy associated with each life phase of the material and to minimize the environmental impact of prototyping we should make the right decisions about materials to prototype with. Does this material have a low embodied energy?

CONCLUSION

This project introduced the *Sustainable Prototyping Life Cycle for Digital Fabrication*, an adaptation from the LCA to support designers' decision making for sustainable prototyping. An online survey, interviews with experts, and a workshop with novice students in design were used to gain understanding on: the possibilities of intertwining bio-based materials with digital fabrication techniques, the current practices, strengths and limitations on sustainable prototyping, and possibilities for introducing the cycle to digital fabrication practitioners. The current practice of prototyping could be improved by understanding the environmental impact of each phase in this cycle (raw materials, manufacturing and distribution, use, and end of life). This paper presents the manufacturing process of several digital fabrication prototypes with bio-based materials following the cycle. Bio-based materials for prototyping is a good start point moving towards a environmentally sustainable making. However, other good practices must be involved in every phase of the cycle such as reducing transportation distances (i.e. buying prototyping materials that are locally manufactured), reducing the energy consumption in machines (i.e. reducing the stand by time which is when the machine is turned on but not working), or making sure we are using energy-efficient machines in our lab. This paper implemented our cycle with bio-based materials. Future works could implement the cycle using common materials, or other bio-based materials that can be adapted and used for digital fabrication, provide a comparison of their environmental impacts, and introduce a tool to quantitatively calculate the environmental impact in every phase of the prototyping cycle.

ACKNOWLEDGMENTS

This paper was supported by the grant from Johnson and Johnson WiSTEM2D Scholars Award. We thank professor Beth Ferguson, class DES165 Industrial Design (Fall 2019) and DES191B Interactive Objects (Fall 2019) for participating in the workshop.

REFERENCES

[1] R. Abhijith, Anagha Ashok, and C.R. Rejeesh. 2018. Sustainable packaging applications from mycelium to substitute polystyrene: a review. *Materials Today: Proceedings* 5, 1, Part 2 (2018), 2139 – 2145. DOI: http://dx.doi.org/10.1016/j.matpr.2017.09.211

[2] Freek V.W. Appels, Serena Camere, Maurizio Montalti, Elvin Karana, Kaspar M.B. Jansen, Jan Dijksterhuis, Pauline Krijgsheld, and Han A.B. Wsten. 2019. Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites. *Materials & Design* 161 (Jan 2019), 64–71. DOI:http://dx.doi.org/10.1016/j.matdes.2018.11.027

[3] M. F. Ashby. 2009. *Materials and the environment : eco-informed material choice*. Butterworth-Heinemann/Elsevier, Amsterdam Boston.

[4] Patrick Baudisch, Stefanie Mueller, and others. 2017. Personal fabrication. *Foundations and Trends® in Human–Computer Interaction* 10, 3–4 (2017), 165–293.

[5] Eli Blevis. 2007. Sustainable interaction design. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '07*. ACM Press. DOI:http://dx.doi.org/10.1145/1240624.1240705

[6] Kristin N. Dew and Daniela K. Rosner. 2019. Designing with Waste: A Situated Inquiry into the Material Excess of Making. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 1307–1319. DOI: http://dx.doi.org/10.1145/3322276.3322320

[7] Kristin N. Dew, Samantha Shorey, and Daniela Rosner. 2018. Making within Limits: Towards Salvage Fabrication. In *Proceedings of the 2018 Workshop on Computing within Limits (LIMITS '18)*. Association for Computing Machinery, New York, NY, USA, Article Article 7, 11 pages. DOI: http://dx.doi.org/10.1145/3232617.3232626

[8] Jeremy Faludi, Natasha Cline-Thomas, and Shardul Agrawala. 2017. *The Next Production Revolution, implications for government and business – 3D printing and its environmental implications.* 171–213.

[9] Jeremy Faludi, Corrie M. Van Sice, Yuan Shi, Justin Bower, and Owen M.K. Brooks. 2019. Novel materials can radically improve whole-system environmental impacts of additive manufacturing. *Journal of Cleaner Production* 212 (Mar 2019), 1580–1590. DOI: http://dx.doi.org/10.1016/j.jclepro.2018.12.017

[10] Kate Till Caroline. Franklin. 2019. *Radical Matter: rethinking materials for a sustainable future*. Thames & Hudson.

[11] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. *Proceedings of the 33Rd SIGCHI Conference on Human Factors in Computing Systems* (04 2015).

[12] GROW.bio. 2016. Grow Bio. (2016). https://grow.bio/

[13] Steven J. Jackson and Laewoo Kang. 2014. Breakdown, Obsolescence and Reuse: HCI and the Art of Repair. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. Association for Computing Machinery, New York, NY, USA, 449–458. DOI: http://dx.doi.org/10.1145/2556288.2557332

[14] Mitchell Jones, Tien Huynh, Chaitali Dekiwadia, Fugen Daver, and Sabu John. 2017. Mycelium Composites: A Review of Engineering Characteristics and Growth Kinetics. *Journal of Bionanoscience* 11, 4 (Aug 2017), 241–257. DOI: http://dx.doi.org/10.1166/jbns.2017.1440

[15] Elvin Karana, Davine Blauwhoff, Erik-Jan Hultink, and Serena Camere. 2018. When the material grows: A case study on designing (with) mycelium-based materials. 12 (2018), 119–136.

[16] Sunyoung Kim and Eric Paulos. 2011. Practices in the Creative Reuse of E-Waste. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2395–2404. DOI: http://dx.doi.org/10.1145/1978942.1979292

[17] Cindy Kohtala. 2017. Making "Making" Critical: How Sustainability is Constituted in Fab Lab Ideology. *The Design Journal* 20 (05 2017), 1–20. DOI: http://dx.doi.org/10.1080/14606925.2016.1261504

[18] F.-D. Kopinke, M. Remmler, K. Mackenzie, M. Mder, and O. Wachsen. 1996. Thermal decomposition of biodegradable polyesters-II. Poly(lactic acid). *Polymer Degradation and Stability* 53, 3 (1996), 329 – 342. DOI: http://dx.doi.org/10.1016/0141-3910(96)00102-4

[19] Suzanne Lee. 2011. Grow your own clothes. (2011). https://www.ted.com/talks/suzanne_lee_grow_your_own_clothes?language=en

[20] Angella Mackey, Ron Wakkary, Stephan Wensveen, Annika Hupfeld, and Oscar Tomico. 2019. Satisfying a Conversation with Materials for Dynamic Fabrics. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 1047–1058. DOI: http://dx.doi.org/10.1145/3322276.3322371

[21] Jennifer C. Mankoff, Eli Blevis, Alan Borning, Batya Friedman, Susan R. Fussell, Jay Hasbrouck, Allison Woodruff, and Phoebe Sengers. 2007. Environmental sustainability and interaction. In *CHI '07 extended abstracts on Human factors in computing systems - CHI '07*. ACM Press. DOI: http://dx.doi.org/10.1145/1240866.1240963

[22] Samantha McDonald. 2016. 3D Printing: A Future Collapse-Compliant Means of Production. In *Proceedings of the Second Workshop on Computing within Limits (LIMITS '16)*. Association for Computing Machinery, New York, NY, USA, Article Article 4, 6 pages. DOI:http://dx.doi.org/10.1145/2926676.2926680

[23] William. McDonough and Michael Braungart. 2002. *Cradle to cradle : remaking the way we make things / William McDonough Michael Braungart* (1st ed. ed.). North Point Press New York. 193 p. ; pages.

[24] Ana Mestre and Tim Cooper. 2017. Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy. *The Design Journal* 20, sup1 (Jul 2017), S1620–S1635. DOI: http://dx.doi.org/10.1080/14606925.2017.1352686

[25] NaturalNews. 2018. Researchers develop blend of bioplastics that can decompose under diverse conditions. (Nov 2018). https://tinyurl.com/ycdass5x

[26] Christian Remy, Oliver Bates, Vanessa Thomas, and Elaine M. Huang. 2017. The Limits of Evaluating Sustainability. In *Proceedings of the 2017 Workshop on Computing Within Limits - LIMITS '17*. ACM Press. DOI:http://dx.doi.org/10.1145/3080556.3080567

[27] David Roedl, Shaowen Bardzell, and Jeffrey Bardzell. 2015. Sustainable Making? Balancing Optimism and Criticism in HCI Discourse. *ACM Transactions on Computer-Human Interaction* 22, 3 (June 2015), 1–27. DOI:http://dx.doi.org/10.1145/2699742

[28] Eldy S. Lazaro Vasquez and Katia Vega. 2019a. From Plastic to Biomaterials: Prototyping DIY Electronics with Mycelium. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers (UbiComp/ISWC '19 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 308–311. DOI:http://dx.doi.org/10.1145/3341162.3343808

[29] Eldy S. Lazaro Vasquez and Katia Vega. 2019b. Myco-Accessories: Sustainable Wearables with Biodegradable Materials. In *Proceedings of the 23rd International Symposium on Wearable Computers (ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 306–311. DOI: http://dx.doi.org/10.1145/3341163.3346938

[30] José Vicente, Rui Frazão, and Fernando Moreira da Silva. 2011. Ecodesign Tools: One basis to operationalize Sustainable Design.

[31] Ron Wakkary, Henry Lin, Shannon Mortimer, Lauren Low, Audrey Desjardins, Keith Doyle, and Philip Robbins. 2016. Productive Frictions: Moving from Digital to Material Prototyping and Low-Volume Production for Design Research. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. Association for Computing Machinery, New York, NY, USA, 1258–1269. DOI: http://dx.doi.org/10.1145/2901790.2901880

[32] Ron Wakkary, William Odom, Sabrina Hauser, Garnet Hertz, and Henry Lin. 2015. Material Speculation: Actual Artifacts for Critical Inquiry. *Aarhus Series on Human Centered Computing* 1, 1 (Oct. 2015), 12. DOI: http://dx.doi.org/10.7146/aahcc.v1i1.21299

[33] Jennifer Weiler, Piyum Fernando, Nipuni Siyambalapitiya, and Stacey Kuznetsov. 2019. MyceliumArtifacts. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion - DIS '19 Companion*. ACM Press. DOI: http://dx.doi.org/10.1145/3301019.3325156