The Environmental Impact of Physical Prototyping: a Five-Year CHI Review

Eldy S. Lazaro Vasquez
Department of Design
University of California, Davis
Davis, CA 95616, USA
eslazaro@ucdavis.edu

Hao-Chuan Wang
Department of Computer Science
University of California, Davis
Davis, CA 95616, USA
hciwang@ucdavis.edu

Katia Vega
Department of Design
University of California, Davis
Davis, CA 95616, USA
kvega@ucdavis.edu

Abstract

This paper presents a systematic review on 494 papers from the last 5 years of the proceedings of the ACM Conference on Human Factors in Computing Systems (CHI) in order to analyze the environmental impact of physical computing prototyping.We present a literature review with the environmental impact of materials, techniques and end of life of materials commonly used in our community. Our results show the increase number of papers on physical prototyping, and materials and techniques mostly used. We discuss different strategies to reduce the environmental impact of prototyping: waste management, energy efficiency in digital fabrication, and using low impact materials. We aim to provoke individual reflection of the environmental impact of our practice as designers, researchers and practitioners. We also support potential actors' behavior change by noticing that isolated decision-making related to materials used can lead in a major environmental impact, even more when we look at a community practice collectively.

Author Keywords

environmental impact; LCA; SHCI; embodied energy; biomaterials; sustainable design; physical prototyping

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI);** *Haptic devices;*

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INTRODUCTION

Sustainability in the field of Human Computer Interaction (SHCI) has been addressed from different perspectives since more than a decade ago. Many studies, discussions and workshops took place around SHCI to identify environmental issues related to HCI [17], [12], [18]; define the scope and role of HCI researchers regarding sustainability [7], [13]; identify challenges the HCI community faces on its aim to address sustainability [21]; search of concrete ways in which HCI can achieve sustainability [6], [5], [20]; and possible reasons of why the HCI community still struggle to have a shared understanding of SHCI [15]. Blevis proposed the notion of Sustainable Interaction Design (SID) [17] which mostly focused in what inventions or systems will become after they are created (i.e., Disposal Phase). Furthermore, there is still a big concern regarding how sustainable and environmentally friendly is the practice of digital fabrication and materials used for prototyping [16].

We made a five-year CHI review to provide an overview of prototyping materials and techniques this community use. In our study, we approach SHCI from an environmental point of view using a method called Life Cycle Analysis (LCA). It facilitates a deeper understanding of all the phases involved creating physical prototypes. We focused in two phases of the prototyping cycle in which researchers and makers are closely involved: Use and End of life Phase.

LITERATURE REVIEW

LCA is a method to evaluate potential environmental impacts of a product, material, process, or activity [4]. This method includes four phases: raw material acquisition, manufacturing and distribution, use, and end of life. For the purpose of this review, we focused in two phases of this cycle in which researchers and practitioners have an active decision-making participation: Use (materials and digital fabrication techniques) and End of Life (reuse and disposal of prototyping materials).

Materials in the Use Phase. The environmental impact of materials derives mainly from the manufacture, use, and disposal of products; and all products are made from materials [4]. Based on this premise, all prototyping materials have an impact in the environment. It is measured by the embodied energy, CO2 emissions and water usage to make these prototyping materials. Ashby [3] defined embodied energy as all the fossil-fuel energy (MJ) consumed throughout the process of making one kilogram of material, from raw materials acquisition and processing of natural resources to manufacturing, distribution (product delivery) and disposal. Tab. 2 shows data collected [4], [8], [24] about the embodied energy, CO2 emission, and water usage on the primary production of materials. We also included data from Eco-Indicator99. The higher the indicator, the greater the environmental impact. The minimum and maximum values vary based on the machines used for manufacturing the materials. The letters "nr" in the table stand for not reported values. Furthermore, we divided common prototyping materials in Metals & Alloys, Polymers, Miscellaneous, and Natural materials (cotton, hemp and mycoboard).

Metal & Alloys. Aluminum has the highest embodied energy (220 MJ/kg) in this group and in all the presented materials in Tab. 2. We find this material in die-cast chassis, foil for containers, mechanical pieces, electronic products. Low-carbon steel is found in pressed-sheet products, and Low alloy steel in gears, springs, tools, and connecting rods.

Polymers. Epoxies materials have the higher embodied energy in this group with 133.5 MJ/kg. It can be found in most of our electronics components, because it is used to encapsulate electrical coils or to cover circuit boards. It is

	Power (watts)	Energy KWh
Trotec: Speedy 400	80	0.0688
Epilog: Fusion Pro 32	60	0.0516
Universal: PLS6.75	75	0.0645
Rolland: MODELA MDX-50	95	0.0817
MakerBot Replicator+	43-182.4	0.037-0.157
Ultimaker 2 Extended	221	0.19006

Table 1: Energy used by common prototyping machines.

also used to make adhesives, for high-strength bonding of dissimilar materials, and to make molds for shaping thermoplastics. ABS and PLA are materials used for 3D printing. PET, PP and PVC can be found in film sheets, synthetic fabric (polyester), motors' chassis, capacitor film, tapes, bottles, etc. Acrylic sheets (PMMA) is the third material with a higher embodied energy in this group. Gloves, belts, pumps, heat shrink tubes, etc. are made with natural rubber (NR) and this material has higher embodied energy than PVC. Furthermore, NR needs from 15 to 20 thousand litters of water to make 1kg of material.

Miscellaneous. Foams and composite materials are part of this group. Flexible polymer foam has the highest embodied energy in this group with 109 MJ/kg. It can be found in stretchable wrist bands, elastomers, and other flexible silicons. Paper and cardboard are recyclable materials, however their embodied energy is high when it is produced for the first time (Tab.2). Plywood is usually used to make product design prototypes or furniture, same as MDF. However, MDF generates 3 more times CO2 emissions when it is made, almost the same value as ABS. Hardwood and glass have almost the same embodied energy and CO2 emissions. Finally, mycoboard (bio-based material) has the lowest embodied energy (4.01 MJ/kg) in Tab. 2.

Digital Fabrication in the Use Phase. The machines we use to prototype add environmental impact to the physical prototyping process. When we use a digital fabrication technique such as laser cutting, 3D printing or CNC machining, we require energy to run the machines. That energy is also added to the total environmental impact of prototyping. Tab.1 shows the power and energy required to run common machines found in a research or prototyping labs. The energy used during idle time, which is the time when the machine is paused or turned on but not being used [9] should be also add to the total environmental impact of prototyping. Energy-inefficient machines can require same energy when the machine is in use and when it is paused.

	Material	Embodied Energy (MJ/kg)	CO2 Emission (kg CO2/kg)	Water Usage (L/kg)	Eco-Indicator (millipoints/kg)
Metals & Alloys	Aluminum	200-240	11-13	125-375	800
	Low-alloy steel	31-34	1.9-2.1	37-111	200
	Low-carbon steel	25-28	1.7-1.9	23-69	106
Polymers	Epoxies	127-140	6.8-7.5	107-322	650
	ABS	90-99	3.6-4.0	250-277	350
	Acrylic sheet (PMMA)	90.00	2.8-3.2	100-264	437
	PET	81-89	3.7-4.1	14.7-42.2	276
	Polypropylene (PP)	75-83	2.9-3.2	189-209	254
	Natural nubber (NR)	64-71	2-2.2	15000-20000	24
	PVC	56-62	2.2-2.6	77-85	170
	PLA	49-54	3.4-3.8	100-300	278
Miscellaneous	Flexible polymer foam	104-114	4.3-4.7	181-544	385
	Paper and cardboard	49-54	1.1-1.2	500-1500	110
	Plywood	13-16	0.78-0.87	500-1000	270
	MDF	11.3-11.9	3.67	nr	nr
	Glass	10-11	0.7-0.8	14-20.5	75
	Hardwood	9.8-10.9	0.8-0.94	500-750	19
Natural Materials	Wool	51-56	3.2-3.5	160000-180000	nr
	Cotton	44-48	2.4-2.7	7400-8200	nr
	Hemp	9.5-10.5	0.29-0.33	2500-2780	nr
	Mycoboard	4.01	nr	nr	nr

Table 2: Embodied energy, CO2 emissions, water usage of common prototyping materials, and Eco-Indicator [4], [8], [24].

End of Life Phase.There are five different options to dispose a material, or physical prototype at its end of first life: landfill, combustion for heat recovery, recycling, re-engineering (refurbish), and reuse [4]. In Tab. 2 we can see the time a prototyping material needs to decompose in the landfill or identify if a material can be recycled or com-

	Landfill	Recycling	Composting	Hazards (laser cut)
Acrylic	400 years	yes	no	-melting -fire hazardous -fumes
Fabrics (nylon, polyester)	30-200 years	no	yes*	-burn -catch fire
MDF (medium density fiberboard)	13 years	no	no	-smoke -high formaldehyde -fumes
Cardboard	2 years	yes	yes	-burn -catch fire
Mycoboard	90 days	no	yes	-burn -catch fire

Table 3: End of life information of common prototyping materials for laser cutting [1], [11].

posted. Furthermore, Tab. 1 also shows the kind of hazards associated with those materials when they are use for laser cutting.

Some prototyping materials are recycled to make the same material again at its end of first life. When that happens, the embodied energy of that specific material reduce, and the CO2 emissions as well. The Eco-indicator value also changes but only when the recycling rate is significant. For example, aluminum has been reported to be 100% recycled, and paper and cardboard can be 70-74% recycled. The table 2 shows which prototyping materials presented in the previous section are recycled and the recycling fraction. Materials reported with less than 0.1% value for recycling were not included in the table.

5-YEAR CHI REVIEW: PHYSICAL PROTOTYPING

Method for Organizing the Literature. By examining the CHI literature in a bottom-up fashion, we identified a group of relevant words which seem to be frequently found when a paper presents a prototype. We adjusted the set of keywords through iterative discussions among the co-authors, resulting in a set of sixteen keywords. We filtered those words from a total of 2998 papers in the following order: 3D print, DIY, laser cut, prototype, wearable, device, tangible, fabricating, make, craft, tactile, shape-changing, electronic, sensor and IoT. The first step was to locate the presence of any of the sixteen keywords in the Authors' Keywords, then by Title and finally in the content of each paper. We made this classification process using Mendeley software to facilitate the work. The second step was to remove from the pool the papers, the ones without physical prototype.In the final step, we first narrow the scope of our analysis by only keeping the papers in which the physical prototype was part of the contribution of the paper, and we determined that by reading the abstract and conclusion of each paper. Second, we looked for what materials and digital fabrication techniques used to build physical prototypes and denoted that information in a spreadsheet [23].

Findings. From the total amount of papers reviewed (2998), we filtered and analyzed 494 papers that had physical prototypes. Our study shows a huge increase in physical prototyping in the last five years at CHI. In 2015, only 37 papers (7.6%) of a total of 486 papers had physical prototypes; in 2016, the percentage increased to 17% with 93 papers out of 545. That percentage slightly increased to 17.36% in 2017 that had 599 papers published. In 2018, the percentage of physical prototypes kept almost the same but the number of papers with physical prototypes increased in 11. In 2019, 145 papers had physical prototypes as part of their contribution, and the percentage increased again to 20.63%.

3D printing has been used in almost 45% of physical prototypes in 2015. This percentage has decrease in 11.8% by 2019. On the other hand, laser cutting only decreased in use from 2015 to 2019 in 3.2%. This digital fabrication technique shows consistency in use in 2016 and 2018 with 18-23% use, but in 2017 there was an increment in use to 28.9%. Other techniques included prototypes created with on the shelf materials, such as wrist bands, valves, electrodes, modules, toys, recycled enclosures, etc. We realized that in 2015, 66% of the prototypes used laser cutting and 3D printing. That percentage decreased in 15% in 2019. Fig.1 represents the materials used during the last five years, from common materials as PLA and ABS used for 3D printing, to Acrylic, MDF, Plywood and Cardboard for laser cutting. The use of wide variety of on-the-shelf plastics (silicone, foam/polyurethane, rubber, or recycled plastics) has increased in 5% since 2015. Other on-the-shelf materials used such as magnets, glass, carbon fiber, metals, fabrics and even natural materials, have increased in use in 6% since 2015.

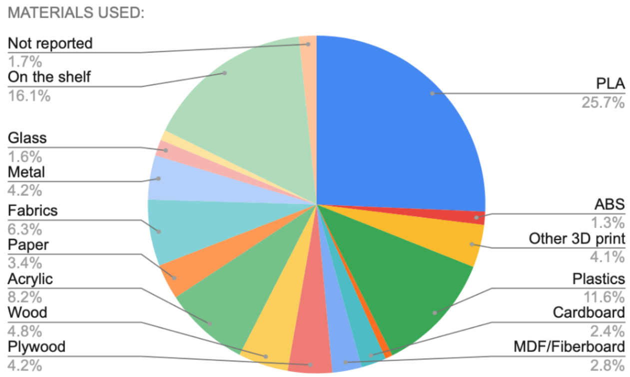

Figure 1: Materials used for digital fabrication to make physical prototypes in the last five-year CHI papers.

DISCUSSION

Based on our study, we noticed an increment of 13.02% in physical prototyping from 2015 to 2019 in the HCI community. The statistics shows that every year researchers and practitioners rely on physical prototyping to show their ideas, systems or tools. We discuss three main findings that emerged from our study: materials and techniques used for digital fabrication, waste management, and recommendations for sustainable physical computing.

Materials and Techniques used for Digital fabrication.

PLA, the most common material used by the CHI community, is a corn-based 3D printing material that biodegrades in up to 90 days only if it is disposed of in an industrial composting facility, and under a controlled composting environment heated at 140F degrees. On the other hand, if PLA waste or unused prototypes end up in the landfill, it will take from 100 to 1,000 years to decompose. Acrylic, MDF/fiberboard, cardboard and synthetic fabrics were the most used materials for laser cutting in this study. Even though, paper and cardboard are recyclable materials, the energy used for making the material itself is high energy intense (54 MJ/kg), even more than to make MDF (11.9 MJ/kg). However, the CO2 emissions generated (3.67 kgCO2/kg) are three times less than for MDF on its primary production (1.2 kgCO2/kg) and almost five times less when it is made from recycled paper/cardboard (0.72 kgCO2/kg). There are some trades that should be done when deciding which material to use for prototyping. For example, if the energy in your country come from wind, biomass, solar (clean energy), then you should pay more attention to CO2 emissions, water usage, and proper disposal of your prototyping materials. Natural materials such as Hemp and Mycelium-based material [22] present the lowest embodied energy (4.01 MJ/kg.) and CO2 emissions from the rest of common prototyping materials. In this study, we only found 9 publications that used clay or wood filaments to 3D print, but 10% of the physical prototypes were made with plastic based materials ranging from bottles, elastic bands, silicone and PVC pipes. Those materials have a really high embodied energy (71 MJ/kg), and in consequence a high environmental impact, specially at their end of life in which they have to be disposed in the landfill and take several years to degrade (Fig.3).

Waste management. Some strategies to address e-waste problems have been explored in the HCI community such as the creative reuse of e-waste [14] or by highlighting makers' ability to repair and reuse artifacts [18]; however, there is not a better way to address this problem than recycling and disposing our e-waste properly. We can adopt circular economy strategies such us design for disassembly (DfD) that allows the reuse of electronic components or a whole circuit if necessary. Transitioning from coin batteries to rechargeable lithium batteries will reduce the environmental impact of our e-waste (less disposal material). Micro controllers such as Arduinos are low-power devices that can be used to read sensors, run motors or turn on LEDs. However, running LEDs at high brightness and for long periods can consume power and drain batteries. We can save power writing a code that drives the LEDs at reduced power, and only for an specific period of time. Furthermore, the use of solar panels to power our devices or to charge our batteries is also another strategy to address environmental sustainability, as much as the use of self-power systems [19], [2].

Recommendations for sustainable physical computing. A big part of the environmental impact of 3D printing (Use Phase) is the energy used while printing [9]. We can reduce the hours of printing by setting up the files with optimal parameters such as adjusting speed, and avoiding a heated bed if not necessary. Thus, we can save energy reducing the idle time. Jeremy Faludi [10] has made a quantitative LCA study to different 3D printers to determine which machines are more energy efficient than others, and he has developed materials for 3D printing that not require to heat the nozzle to extrude the material in order to lower the energy consumption of 3D printing [10].

Recycling waste processes play an important role in research labs or maker-spaces. That's is why having proper waste disposal practices will help to reduce researchers' environmental impact. Having separate waste bins in a lab (recycling, composting and landfill bin) should be mandatory, adding an e-waste bin. The use of electronic components comprises 42.1% of the materials used in physical prototyping in the last five years in CHI venue. If all the e-waste generated in this period of time would has been disposed properly, we could have reduce our environmental impact.

We also discuss the increasing use of on the shelf materials for prototyping, which make the Disposal Phase of materials more complicated because those products (belts, elastic bands, stretchable wristband) have various materials combined in one, and for that reason they all should be disposed in the landfill trash bin not allowing recycling or composting processes. One way to reduce the environmental impact of those materials would be making longer lasting products, prototypes or designs that embrace the principles of durability, reparability, upgradability and mainly reusability.

Finally, we recommend practitioners to identify local recycling facilities in their institutions and city. For instance, most of the counties in the US have composting and recycling facilities where we can leave our prototyping materials' waste. Sometimes it is also possible to find recycling and composting facilities on campus.

CONCLUSION AND FUTURE WORKS

Creativity, innovation and research lead us to fabricate different objects that envision the future of technology. However, this creation come with a huge responsibility on the environment impact that these materials and techniques unchain. This project presented a 5 years review of the CHI community in the fabrication of physical prototypes. The main contribution of this paper is to provide a guideline to understand that impact of our practice and provide recommendations that could be incorporated in our labs on alternative materials, waste management, digital fabrication machine usage and materials selection. Future works envision to provide a software tool for practitioners to analyze the individual impact of their fabrications.

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