HowDIY: Towards Meta-Design Tools to Support Anyone to 3D Print Anywhere

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ABSTRACT

The promise of anyone being able to 3D print anywhere relies on both technological advances and incremental shifts in social organizations to trigger changes in human behavior. While much research has focused on how people learn aspects of predefined printing processes, such as expressively utilizing particular design-software and fabrication-machinery, this work explores how anyone may gain an understanding of what can be 3D printed through dynamic-processes in computationally-guided exploration of online resources and 3D printing facilities. Investigations surrounding online printing services reveal accessible 3D printing processes that do not require end-users to have experience with design-software or fabrication-machinery, only requiring end-users to specify printable ideas. We present these accessible printing processes alongside associated technologies in a meta-design framework for supporting end-users' specification of 3D printing ideas. Informed by this framework and a series of formative studies, we designed the website HowDIY to introduce anyone to 3D printing by encouraging and facilitating the intelligent exploration of various online resources. HowDIY was deployed over several weeks with diverse newcomers to 3D printing, validating that intelligent user interfaces can support anyone to participate in the utilization and design of 3D printing tools and processes.

KEYWORDS

3D Printing; Meta-Design; Broadened Participation

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1 INTRODUCTION

The future of anyone 3D Printing from home, which has been speculated to transform manufacturing and consumerism [6, 8, 54, 60], requires not only technological advances in 3D printing but also incremental shifts in social organizations to trigger changes in human behavior [24]. The practice of 3D Printing generally requires three steps: 1) Obtain a design file, 2) Convert that file into printer-specific machine code, and 3) Operate the printer to create the end-product. Presently, many learn this practice through the trial-and-error operation of printers or through human-guidance in place, developing tacit and embodied knowledge of what is *printable* [22]. Previous research has made learning this practice more accessible online by facilitating *in-situ* feedback of designing printable files (i.e. step 1) [20] and by supporting the remote sharing of printer status [48] (i.e. step 3). While these tools make some aspects of the processes attainable, alone they still require that newcomers have proximal access to printing machinery and learning resources.

Proximal printing services, brick-and-mortar shops, have been shown its potential to lower the barrier of entry to 3D printing by allowing end-user to learn what is printable without requiring technical knowledge of printer operation and maintenance [13, 15]. Online services operate similarly, where end-users specify printable designs online for distal operators to fabricate and ship. However, this specification process is not trivial, as 3D printing is not *What-You-See-Is-What-You-Get* [11], and design files themselves often do not express design-intent of what is being printed [15, 36], requiring end-users to employ broader embodied and sense-making processes to specify their design ideas into printable files [22]. In our analysis of online printing services, we found that these services serve as an entry point for many to begin 3D printing, while their specification-interfaces often assume end-users possess technical knowledge of printer operation, which may impede many from accessing these services as an entry-point to printing practices. To support anyone to print from anywhere through online services, systems must be designed to afford anyone to interact and collaborate with these online services while learning the needed, encapsulated knowledge about printing processes. In this paper, we investigate how online printing services, where anyone can form a collaboration with distal printing practitioners, can empower printing from anywhere.

This echos themes from research in *Meta-Design*, which demonstrates how end-users consume and learn to develop digital artifacts

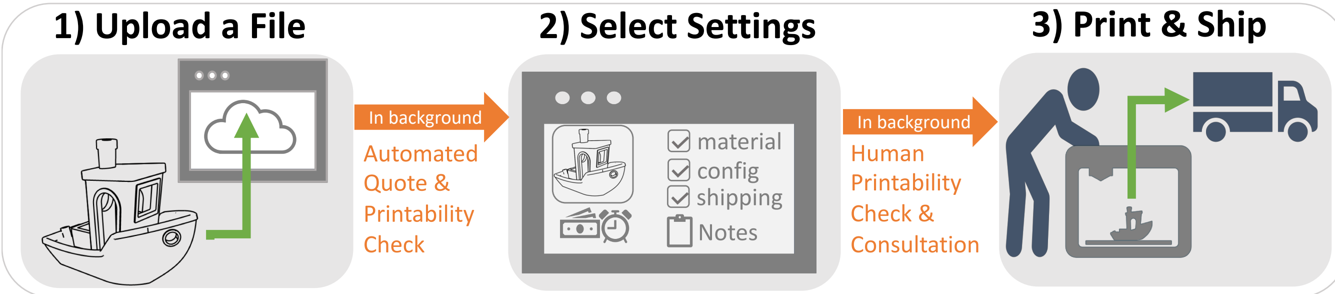

Figure 1: Anyone can print via Online 3D Printing Services by uploading 3D files, then specifying print-configuration options specific to each service. Users may be guided by distal practitioners to navigate digital and physical aspects of designing, but often these practitioners are hidden unless actively sought.

through *Cultures of Participation* that shift creation by large contributions from few users to small contributions by many users [24, 25, 28]. We investigate how meta-design systems relate not only to the development of digital artifacts, but their subsequent fabrication. Through Fischer and Giaccardi's meta-design framework [25], we argue that existing meta-design systems for 3D file generation and fabrication should be situated in overall printing process, as end-users may not easily find associated tools without guidance from humans or intelligent systems [15]. We demonstrate the potential of these situated meta-design systems with HowDIY, a website that introduces diverse end-users to various 3D printing practices by supporting their specification process. In a purely-online evaluation with 22 diverse participants with no prior 3D printing experience, we found that HowDIY could successfully introduce 3D printing practices to newcomers, who later demonstrated knowledge of printing processes acquired through utilizing HowDIY. HowDIY users demonstrated an ability to effectively seek consultation from 3D printing services without always specifying 3D files, and to find printable designs that interested them. We conclude by discussing design-implications for 3D printing meta-design systems, facilitating printing for anyone, anywhere.

2 META-DESIGN: END-USER DEVELOPMENT OF TECHNOLOGICAL ARTIFACTS

The creation of accessible technologies does not guarantee their adoption into everyday lives and practices. Adoption, instead, is incremental, manifesting through changes in social organizations and human behavior as technologies become more embedded and situated in everyday life and practices [25, 28, 35]. This does not mean transferring the responsibility of design to the end-user, but to enable domain experts to support their practices through design [27]. Meta-design supports a dialogue between end-users, meta-designers, and technological artifacts so that all move beyond their original states [25]. In this paper, we consider 'design' to include both the dialogue for creating 3D designs and the dialogue for fabricating these designs, with their inter-dependencies.

Evolution of meta-design systems shift focus from *"large efforts of a small number of people"* towards *"small contributions of a large number of people"* [25] in cultures of participation. Effective meta-design can facilitate users progression from passive consumers of designed technologies towards well-informed users and effective meta-designers, informing meta-design tools in the process [24]. Fischer and Giaccardi outline how meta-design encompasses three levels of design: **1)** Designing Design, **2)** Designing Together, and **3)** Designing the "*in-between*" [25]. The first level serves to help end-users establish the necessary conditions for successful design, helping approach the challenging task of fully anticipating end-users' *needs and tasks* at design-time. The second level supports how designers and users may *collaborate* on design activities, both at use time and design time, to address unresolved discrepancies between design-intent and the resulting design with respect to the aforementioned needs and tasks. The third level aims to support or create social networks to foster participation with design technologies, facilitating embodied sensing, emotioning, and "affective" activities. In the next section, we convey how existing 3D printing literature relates to this meta-design framework.

3 RELATED WORK: THE THREE LEVELS OF 3D PRINTING META-DESIGN

End-users may face many challenges to begin 3D printing processes [15], while engaging in 3D printing processes [37], and end-products may not always match their expectations [11, 48]. In this section, we outline how research about 3D printing end-users and challenges to 3D printing relate to Fischer and Giaccardi's meta-design framework, granting a more-holistic understanding of how to broaden participation with 3D printing.

3.1 Designing Design: Imagining and Planning What to Print

Designing Design for 3D printing entails how people design or reuse designs to fabricate, which does not require utilizing traditional CAD applications. Many barriers exist to 3D printing even before interacting with any printing programs, machines, or facilities. Berman et al. outline workflows and challenges towards specifying 3D printing ideas in formal collaborations with 3D printing services that insulate clients from many technical details of machine operation and maintenance [15]. In this paper we investigate similar workflows for 3D printing via services, shown in Figure 1, to support anyone to participate with 3D printing without requiring that

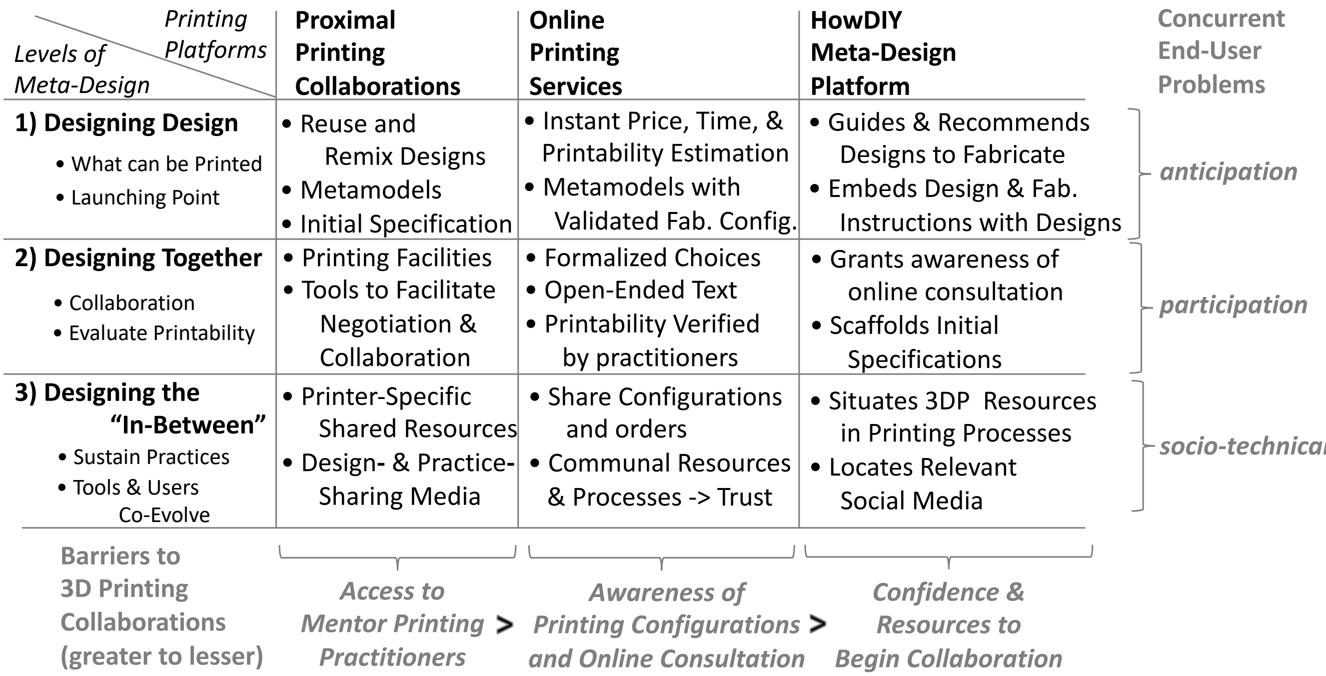

Figure 2: Each level of meta-design (*rows*) corresponds to different technologies that may support broader participation in 3D printing by addressing end-user problems. Each *column* from left to right represents further abstraction and encapsulation of 3D printing processes, supporting creation of digital-designs and physical-fabrications with fewer overlapping barriers.

all end-users participate with CAD programs and printing machinery. This allows us to present 3D printing meta-design challenges that emerge irrespective or particular programs or hardware.

Reuse and Remixing: Many print existing designs or modify them to make printing more expressive, more expedient, or more accessible [31]. In this process, end-users download designs from 3D printing file-sharing platforms like Thingiverse to modify them before printing [29]. Similarly, 3D scans of objects can be utilized in this remix process [61]. Various 3D file search and retrieval systems may be employed to facilitate reuse of these designs [9, 14, 38, 46, 47], informed and situated in end-users' environments [7, 59].

Metamodels: Previous research demonstrated how meta-design may apply to the digital-design of printable objects, where derivatives of metamodels can be designed by specifying simple parameters (e.g. text and size) to generate a 3D file that matches a pre-coded template (i.e. the metamodel) [43, 68]. When Thingiverse added the Customizer tool, which supported the sharing of metamodels and consequent design-generation, the number of users on the platform rapidly increased [29]. Metamodels can broaden participation in 3D design, but alone may not be enough to facilitate broader participation with 3D printing [16, 65].

Specifications: Design and Printing services, from designers-for-hire to crowd-sourced designs, require that end-users specify what they wish to print [15, 53]. Shewbridge et al. investigated what people would print at home with an imaginary "*faux 3D printer*", finding that many wanted to replicate or modify existing objects in their environment. However, end-users expectations of what to print are dependant on their previous exposure to real 3D printing processes [15, 50]. It is important to consider that the end-product is more than just geometry, but has material qualities dependent on the printing configuration [11]. Additionally, capturing accurate measurements for a particular specification may often be challenging without assistance or training [41]. Regardless of material, newcomers to 3D printing have been shown to value their participation in the printing process [50]. However, participation in printing processes is not trivial as design-intent is often not conveyed in 3D file formats [36], and there are often miscommunications conveying design-intent to others [15]. Additionally, many can not find relevant online resources for fostering communicable 3D printable design specifications without guidance [15]. Designing Design supports end-users specification of design-intent, which is necessary for communication within *any* 3D printing process.

3.2 Designing Together: Collaboratively Developing Print Specifications

Designing Together involves collaboration between end-users and others to refactor and refine ideas until they become printable. Evaluating an idea's printability involves broader embodied and collective sense-making tasks [22]. Certain designs may only be printable by certain machines, materials, and practitioners. *Designing Together* entails helping people find the needed expertise and facilities to print, and then facilitating the needed collaborations and negotiations to refactor how and what to print.

Facilities: What is printable depends on the available tools and expertise available. Based on initial specifications, initial facilities should be recommended to end-users, as newcomers often have difficulty accessing printing facilities on their own [15, 37]. As many newcomers may be shy to interact with experienced printing practitioners [7, 37, 59], any meta-design system should help encourage and initiate collaboration.

Communication: Berman et al. investigate barriers and challenges to 3D printing service collaborations [15]. Some communication is necessary as printing practitioners may often mistake aspects of end-users design intent when collaboratively printing a given design [15, 23]. Communication may be in-person or remote (e.g. email or web-chat), even situated in 3D printing practices like CAD procedures [5, 20].

Verification: Similar to how a compiler gives a designer feedback in the form of warnings or errors, meta-design systems should guide end-users around common mistakes and help them navigate trade-offs within their design and their chosen printing configuration [18]. This could be provided via human-human consultation, but may also be facilitate by intelligent assistants and crowd-sourced social media [52, 53]. Similar to how programmers may utilize Stack Overflow to ask questions and find answers, future 3D printing meta-design media may help users verify their designs and printing configurations [67].

3.3 Designing the In-Between: Validation and Sharing of Printing Practices

Designing the In-Between entails how end-users may share their experiences with the world. We focus on how printing tools, social media, and online printing services can serve as the *in-between.*

Tools: Ludwig et al. investigated how people operating 3D printers may share aspects of their practice by sharing logs on Twitter collected by various sensors integrated into a 3D printer [48]. Presently, there are not standard for defining printing capabilities (e.g. a Resource Description Language [58]) or sharing logs [12]. Standardizing similar log-collection and -sharing software in printers may help foster a Internet of Practices where operators can better share every detail of how they appropriated their machinery [48], but this is not the only step of the printing process.

Validation: End-users need to be able to evaluate and contribute opinions relating to collective trust towards particular printing facilities, tools, and processes. Different printing processes and printable products may be more accessible to be designed or fabricated by different users, becoming more accessible with shifts in psychologies and societies [64]. Transparency, the ability to gain knowledge of why people performed actions and why certain tools were utilized in a practice [44], is necessary at each step of the process to help people become printing practitioners. End-Users sharing successful prints, and engaging documentation of how the print was successfully made, may help facilitate printing practices. Also, intelligent interfaces that help people find designs and processes relevant to end-users' interests may help anyone find the appropriate shared documentation. For example, one could capture images of a 3D print or similar real-world objects to find relevant 3D designs, how they were made, and how they could quickly fabricate copies through a service. As present Thingiverse-users gain insight into design creation and functionality [5], future meta-design systems could help crowd-source annotations,answer questions relating to particular design-ideas, and inform verification systems described in Section 3.2.

4 EXPLORATORY STUDIES

As a first step in our exploration of meta-design for 3D printing, we conducted three studies focusing on how people may utilize online present 3D printing services, and how service-staff may imagine facilitating anyone to print.

4.1 Content Analysis of Online Printing Services

To better understand how the present landscape of online 3D printing services may facilitate meta-design practices without aid from social media, we conducted a qualitative content-analysis of 36 online 3D Printing services in Summer 2020. Online 3D printing services were identified by searching on Google based on related keywords, and recording all names that occurred directly in searches and in related webpages (e.g. blog posts listing top online printing services). Coders reviewed each website and coded for the functions the website served. This including uploading two 3D files to websites that offered that functionality and walking through all steps of ordering before payment is required. One of the uploaded files contained thin walls and a non-manifold mesh to see if the service would automatically inform the client of these common printing-file errors. In total, we reviewed 33 websites, of which six did not have a printing interface but just an email contact form. The high-level results of the remaining 27 websites are shown in Table 1.

4.1.1 Designing Design: Instant Verification of Printable Ideas. All interfaces observed involved the following process, as illustrated in Figure 1: 1) Upload a 3D File, 2) Choose Design Adjustments and Fabrication Options, and 3) Order Print. However, as discussed in Section 3.1, a 3D file may not describe all aspects of users' specifications or design-intent. There are elements of design-intent, influenced by both geometry and fabrication options (e.g. material) that are implicit to these interfaces but require significant background in 3D printing to understand within the contexts of printability. Of the 27 services that had an interface for uploading 3D files, all provided immediate prices but only a few offered immediate automated evaluation of printability. Some offered affordances for uniformly scaling of the geometry and re-orientation of uploaded files, but often the effects of these operations were not transparent. Many required selections like material and printer type lacked descriptions or images for end-users to gauge trade-offs.

4.1.2 Designing Together: Notes and Chat-Boxes. Some printing services offer ways to discuss ideas before printing, but these chat interfaces are often relegated to a secluded corner of the screen. Some services allow for writing notes or uploading files while ordering, but this is not a required step before ordering a print and feedback is only given after payment. All services surveyed do not provide clear affordances for expressing design-intent in addition to 3D files, so services may often print files that do not match the intent of a less-experienced user. However, many services do require some operator-verification before printing a clients order, although not all services explicitly state this when placing an order. Some

	Capabilities	Craftcloud	Shapeways	Sculpteo	3D Hubs	i.materialize	makexyz	Xometry	Protolabs	Jawstec	Stratasys Direct	Treatstock	Fast Radius	Voodoo Manufacturing	Fathom	FacFox	SD3D	3Diligent	Jomatik (formerly Trinkle)	Kraftwurx	Beta Layout	WeNext	HK3DPrint	AutomotivMFG	RapidMade	Makeprintable	GoProto	You3DIT
Instant Design Adjustments	Online Quote Interface	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	No Account Needed	●				●	●			●		●					●		●	●	●					●		●
	File Verification Tools		● (red)	● (red)	●											● (red)							●			● (red)		
	Scaling Adjustment Tools	●	●	●		●	●										●	●	●							●		
	Orientation Adjustment Tools		●	●	●				●										●									
Fabrication Options	Customize Slicing Settings	●			●		●					●	●	●			●					●			●			
	Images of Material Options	●	●	●	●	●	●		●					●					●	●					●			●
	Descriptions of Material Options	●	●	●	●	●	●	●	●	●		●		●	●	●			●	●		●			●	●		●
	Direct Choice of Printer Type			●	●	●	●	●	●	●	●		●		●	●	●	●	●			●		●	●		●	●
	Multiple Manufacturer Options	●					●	●				●						●										
Social Feedback	Chat with Service (before order)	●	●	●	●			●		●	●			●		●	●					●						●
	Notes for Printing (during order)	●			●			●	●	●	●	●	●	●	●			●					●	●	●		●	
	Additional File Uploads (not 3D)							●	●	●	●		●		●			●						●			●	
	On-Site Design Catalogue		●			●						●							●	●								●
	Sharable Order Link	●	●	●		●	●				●																	

Table 1: Online 3D printing service interface capabilities. Black dots denote capabilities of each service.

also explicitly state that they repair 3D files that contain common errors, as shown by the red dots in Table 1, although many may do this hidden from the end-user. Regardless, the verification process is not transparent to end-users. Five of these services personally called the telephone number of the researchers to see if they needed help with their order.

4.1.3 Designing the "In-Between": Sharing Designs and Print Configurations. A few of the services provided a catalogue of designs that could be selected and printed, verified to be printable by the service or its users. Some even provided means to distribute metamodels for end-users to generate personalized designs online. Additionally, some services provided affordances to create and share links towards a duplicate order with your specified configuration and notes.

4.2 Social Media Analysis of Printing Services

To better understand how people presently collaboratively print online, we conducted an analysis of social media comments that mentioned online 3D printing services. We scraped all mentions of the 36 identified services from the following three online platforms: Thingiverse [14], Reddit [4], and the 3D Printing Stack Exchange [2]. To systematically classify content of conversations surrounding 3D printing services, we first created a separate sample of 471 comments evenly distributed amongst the 3D printing services (167 from Thingiverse, 54 from Stack Exchange, and 250 from Reddit). Three researchers conducted an open coding analysis [63] to identify frequent reasons people mention 3D printing services online. From these observations, we iteratively developed a coding scheme until it converged on this subset of comments. To validate this scheme, we then created another sample of 301 comments (127 from Thingiverse, 162 from Reddit, and 12 from Stack Exchange). We utilized the Fleiss' Kappa score and found strong agreement in the coding of online social media posts (κ=0.7984). Below, we outline the key findings of this social media analysis along the three levels of meta-design.

4.2.1 Designing Design: Services Seed End-User Introductory Participation. People mentioned using services because *"I don't want to feel overwhelmed early on"* (Stack Exchange User). While services were utilized for a wide range of 3D printing applications within these comments, most were oriented towards personal projects, not commercial applications. Many mentioned utilizing learning resources and design guidelines provided by services to obtain printable files, some even uploading files to verify whether or not they were printable.

4.2.2 Designing Together: Distance Matters for Collaboration and Pricing. 3D Printing services were often recommended for newcomers, so that they could start printing without the initial overhead. Many mentioned it cost less than buying printers initially (e.g. *"If you do not have the tools to fabricate this component yourself, but have a 3D model available, I would suggest getting someone else to*

3D print it for you" - Stack Exchange User). Additionally, for more *casual* printing users, they were often encouraged services as a way to get a print done without having to learn many technical details about printing. Many use services without owning a printer themselves (e.g. *"submit files for printing–I don't own a 3D printer either"* - /r/3DPrinting User). Online services often help clients determine printability of their ideas, similar to Berman et al.'s observations of proximal printing services [15]. Sometimes services, when receiving messages in orders, would say they cannot print these items (e.g. *"[services] passed on the project... [saying] "those requirements will not be possible on our equipment"* - Stack Exchange User). Commenters mentioned preference for proximal services over online services when available, citing better consultation experiences and better prices (e.g. "*For more complex designs, I would recommend working with a local manufacturer*" - Reddit /r/SmallBusiness User).

4.2.3 Designing the "In-Between": Earning Trust and Community-Building. Some referred to these printing services for communities that have formed around them (e.g. *"Some quick notes on my build to share with the community [about materials]..."* - Thingiverse User). Many commenters of various backgrounds mentioned visiting a service's forum, where users could discuss printing practices. However, many mentioned issues where services were damaging other online 3D printing communities, particularly by violating designers' intellectual property rights (e.g. *"I did not give permission for them to sell this design"* - Thingiverse User). Many users on Thingiverse explicitly ask for their designs not to be uploaded on these service's design-stores. To facilitate broader participation with fabrication (meta-design) services, all parties must trust them. For anyone to be confident in utilizing a service, they must trust the service to fabricate satisfactory to the expressed intent. This trust can be built by sharing success stories on social media, however many expressed having difficulty distinguishing between failures in digital design and failures in fabrication (e.g. *"I don't think it's the designers fault but rather the printers I guess?"* – Thingiverse User). Some commenters on Thingiverse explicitly asked for measurement details (e.g. *"What are the exact measurements so that I know [i.materialize] will print the correct size. I have never 3D printed anything and have am really new to this process" - Thingiverse User*). Verification of printability in the previous level is essential for establishing end-user trust. While proximal printing services were often preferred by commenters, these service-providers commented that many end-users did not trust them until they joined communities on social media (e.g. *"It is EXTREMELY hard to get clients away from either service [Shapeways and Sculpteo] because that is the way they have always done it"* – Reddit User). For end-users to trust services, and for services to be found and trusted by end-users, systems should be in place to guide end-users to services with affordances to evaluate their trustworthiness.

4.3 Participatory Design of an Introductory 3D printing Website

With the goal of broadening participation with 3D printing via a single intelligent website, we approached five experienced printing practitioners (3 Male & 2 Female, ages 19-29), most having experience running printing services where they help newcomers at least once a week.

4.3.1 Card Generation - 3D Printing Concepts. The practitioners first wrote on cards (i.e. *Card Generation* [17]) all the concepts that should be conveyed to any newcomer when beginning to print in collaboration with a service. All included a walk-through of how someone could print through their service, including critical requirements with surrounding knowledge, such as requirements for a printable 3D file. All wanted to convey that 3D printing takes time to complete, as some newcomers frequently wanted prints faster than feasible. They suggested that users should see examples of what to print, with notes on price and fabrication-duration, to help recruit more newcomers. Many mentioned that displayed examples should be personalized to the newcomers' interests, with searching capabilities to browse through different example projects. Some mentioned displaying images of example prints from the service, with the ability to compare products of different materials and printer-types. Some mentioned having a glossary of many common 3D printing terms (e.g. support material, orientation, etc.). All mentioned showing links to webpages they frequently utilize when planning 3D printing projects, such as Thingiverse, and to social media channels of 3D printing practitioners. They all mentioned that there should be mechanisms for promoting the newcomers' prints through the service on social media.

4.3.2 Card Sorting - Personalization versus Exploration. They were then asked to organize these cards as they would appear on a website (i.e. *Card Sorting* [21]) with thinking-aloud solicitation. Most organized concepts in one large-scrollable page, displaying quick shortcuts to quotation systems, 3D printing basics, FAQs, and contact information for services. There would also be *recommended* designs featured on the side. There would be ways to curate, or "*save*", and search through different designs. This layout would present a lot of information all at once, ensuring that newcomers have avenues to see all the needed information, but burdening them with processing the order of how all the steps are connected in the printing process. Two described *Wizard*-like interfaces [30], asking users to enter information in a prescribed order to determine how to introduce them to 3D printing. For example, if someone says they are not experienced in CAD and do not wish to learn CAD, they would be shown downloadable or easily-customizable 3D designs before CAD tutorials. These mentors referred to their imagined website as providing tailored 3D modeling and printing tutorials tailored to user-preferences and printing-desires, similar to *DuoLingo*. This layout theme would place less of a burden on users by only showing information thought to be relevant at a given time, but risks hiding information that newcomers could utilize or could pique newcomers' curiosity. In the next section, we describe how personalized versus more open-ended guidance are balanced in the introductory 3D printing meta-design platform HowDIY.

5 DESIGN OF HOWDIY

Exploring how to introduce newcomer end-users to 3D printing through only online guidance, we designed the HowDIY meta-design website. We iteratively designed the system, seeking feedback and usability scores from many pilot users. In this section, we describe the design of the HowDIY meta-design platform as facilitated by intelligent systems.

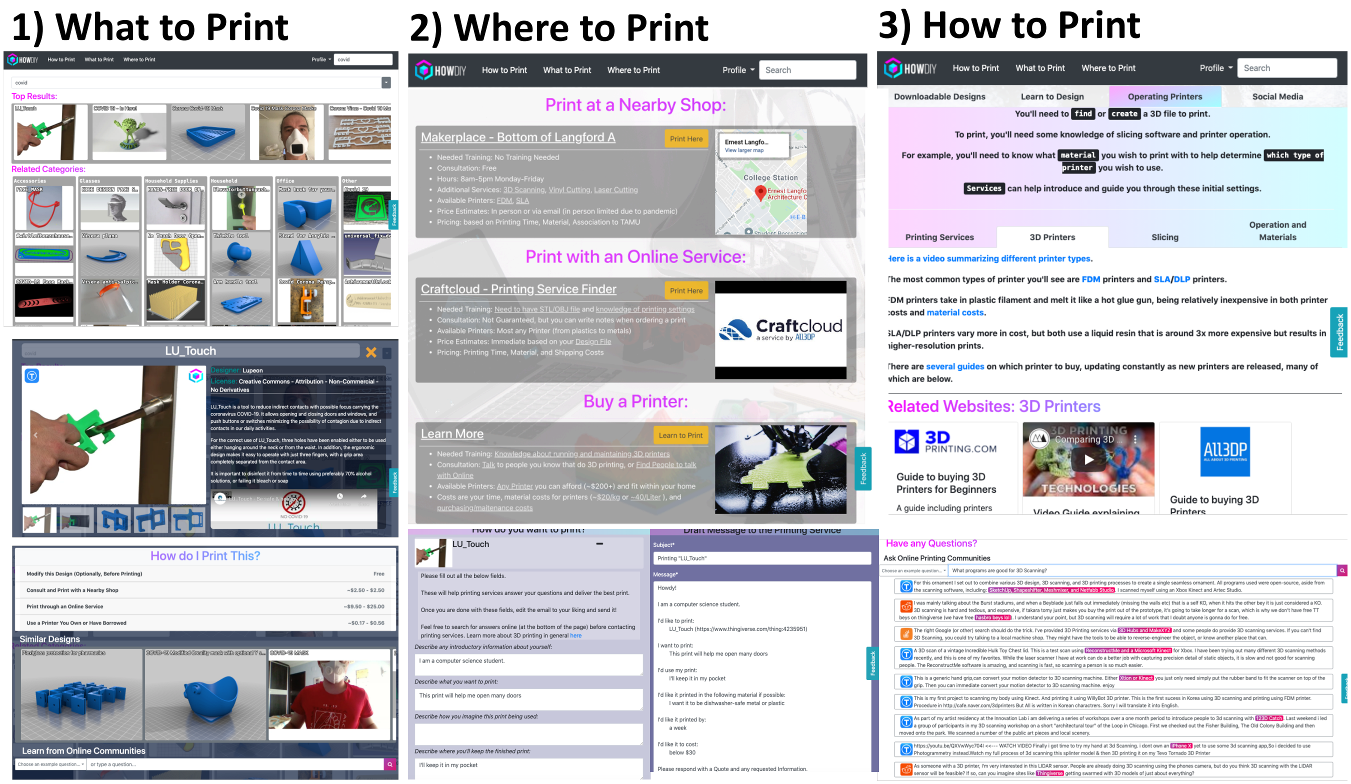

Figure 3: HowDIY contains 3 interlinked webpages corresponding to levels of meta-design, employing intelligent user interfaces to help anyone learn about opportunities to 3D print online: 1) content-based recommendation and queries identify what can be printed, 2) directory of recommended printing facilities and guided specification help initiate collaborations, 3) curated library of resources and an intelligent closed-domain question answer system help identify websites and social media to learn and share about 3D printing online

5.1 Home Page: HowDIY Components as they relate to Levels of Meta-Design

When end-users first enter the website, they are guided towards questions relating to 3D Printing: 1) What to Print, 2) Where to Print, and 3) How to Print? Rather than assuming the user's extent of latent expertise in 3D printing (e.g. CAD skills), these questions help guide the user to areas of 3D printing that will help them progress towards participation. Each question focuses on a different level of meta-design, listed in the same order above, but all questions encourage users to explore all levels are interdependent and concurrent.

5.2 What to Print?: Recommendation and Search Interface for Printable Designs

This interface focuses to the level *Designing Design*, helping end-users find printable ideas related to their interests, and guiding them towards avenues for participation with design and printing. When first visiting the website, the user has to enter a single text field describing their interests. Much like how a hardware store clerk may help clients navigate and refactor vast problem- and solution-spaces [26], content-based recommender systems and design-browsing interfaces in HowDIY help newcomers gain awareness of what can be printed.

Browsing Interface: The goal of the browsing interface is to show many example designs of *what* can be printed, hoping that users will click them to discover *how* to print. Each design is represented by the same thumbnail that is utilized in Thingiverse, where on hover it will display *"How to Print?"*. The top row is the typical "best" results, showing the most popular recommendations or query-results. Below are 81 columns representing Thingiverse category-specific transpositions of the search results, so that users may better understand the wide variety of domains that relate to their interests or query. These categories are sorted by the number of appearances in the overall results, so relevant categories are displayed first without extra horizontal scrolling. One query can have one intended meaning but can be easily be confused by search interfaces for other meanings. Showing the array of category-columns can help users disambiguate these multiple meanings that are not as obvious by viewing a one-dimensional list of results. If the user scrolls beyond the bottom of the screen, there are direct links to elements of HowDIY's one-page library of online resources to "Visit other Model-Search sites", "Hire a Designer", or "Learn to Design". Similar links to locations of this library are situated throughout HowDIY, including individual design views.

Indexing Designs: Content-based recommender systems and querying was performed by creating a Approximate Nearest Neighbor (ANN) model (with Hierarchical Navigable Small World graphs [49]) for all of Thingiverse and each category on Thingiverse. Vector representations of design-text were created by performing TF-IDF on the corpus of design-text which served as weights in a weighted sum of each Word2Vec (W2V) word vector [56] present in the metadata, which has been shown to produce good document-level vector representations [32, 33]. Images and 3D File representations in the same W2V TF-IDF space were predicted by neural network models similar to Berman and Quek [14].

Query Inputs: Queries are directly converted into the vector space for ANN queries, while only a random subset of terms from the user-written interests are queried for recommendation views. Recommendation per design (e.g. *"similar to this"*) are also computed by querying the content-vectors against all the documents. Based on design guidelines for recommender systems [39], we added diversity in the recommendations per design by querying each category separately and inserting top results from multiple categories into the final recommendations. Results from user-queries are collected in a larger number than shown, which are then by default sorted by a normalized popularity score (i.e. number of views divided by number downloads per design) and items containing exact terms from the user's query are moved to the front. This helps top results all appear both relevant and printable, as they are indirectly validated by the Thingiverse community.

Design-View *Thingiverse-Metadata*: Clicking *"How to Print?"* on any design-card will elicit a overlay screen showing detailed information about the design from Thingiverse and information on how to print this file with price estimations. A gallery of author-uploaded images is shown, featuring a Thingiverse thumbnail that links to the Thingiverse design url. There is also a button to view all 3D files in the browser. This 3D file viewer renders the file with multiple multi-colored directional light-sources, and rotates the 3D object. This helps users not confuse the color of the render as the color of the final print, and helps them with the often unintuitive challenge of changing the view-port [37]. In addition to the images and 3D viewer, all other Thingiverse textual metadata (e.g. design description) is compressed to a single scrollable text box. License Names designated by the author and links added by HowDIY are displayed at the top of this box.

Design-View *How to Print*: Below the Design-View contents generated from Thingiverse Metadata are HowDIY generated detail on How to Print the design. There are four options, each with a dynamically calculated price: **1)** *"Modify this Design"* gives links to download the design files and links to the HowDIY library on how to modify designs in introductory CAD programs (e.g. TinkerCAD); **2)** *"Consult and Print with a Nearby Shop"* describes nearby shops and links to the "talk" page (Section 5.4); **3)** *"Print through an Online Service"* gives a link to the "talk" page but also gives a shareable links to online printing service with designs pre-loaded for price estimation and ordering; **4)** *"Use a Printer You Own or Have Borrowed"* provides a link to download the files, and several links on how to purchase and operate 3D printers in HowDIY's library. Each of these options starts collapsed in an accordion-view, with the collapsed view showing the above options and estimated prices for each options. Design modification is always free, while the other prices are calculated by the volume of the mesh. For the online-service cost, the same API that creates a pre-uploaded order link also is utilized to eventually give a more-exact price range for the designs' models. While these prices are usually fairly accurate, it should be noted that some designs only require a subset or require multiple copies of one mesh, which is not presently taken into consideration in HowDIY.

Design-View *Recommendations and Closed-Domain Question-Answer System*: The average vector representation of the design text and files is combined to query each category's ANN individually. Only taking at most two per category, the closest neighbors are sorted into one list that is rendered in a "Similar Designs" list similar to the overall search results. In addition to designs, HowDIY also contains a large dataset of social media comments similar to Section 4.2 from Reddit, the 3D Printing Stack Exchange, and Thingiverse. All comments were employed in a Closed-Domain Question-Answer (CDQA) system that retrieves a large sample of webpages with comments that may likely contain an answer to a given user-question (i.e. TF-IDF similarity like DrQA [66]),then employs DistilBERT [57] to read and score the answers within these webpages. The interface for this system appears in every non-homepage view of HowDIY, with slight variations in shown example questions in drop-down menus. It is difficult to ascertain insightful questions without a good understanding of the domain [26, 55], so example question may help users understand the types of questions that may be asked. Upon asking a question, the user is shown a link to the *"How to Print"* Page and several text snippets with the predicted answers highlighted.Each design view CDQA interface has example questions tailored to the particular design. These questions were informed by Alcock et al.'s taxonomy of questions asked on Thingiverse [5]: "What materials should I use to print X?", "How can I use X?", "What programs can I use to design X?", and "What are challenges when printing X?". Having these example questions can give newcomers a starting point to understand how and why the design was made.

5.3 How to Print: A Library of Online 3D Printing Resources

Based on the collection and organization of 3D Printing websites gathered in the card-generation study, we created a dynamic one-page library of various online web resources related to 3D printing. The focus of this library-interface is to encourage end-users to find, explore, and participate in various online communities surrounding 3D printing (e.g. the "In-Between"). The page has five sections, from top to bottom: Instructions to navigate HowDIY, Printing Process Steps, Categorical Tabs, Related Websites, and a CDQA interface. The HowDIY navigation instructions are static instructions detailing the parts of this page, and explaining that users only need to obtain a 3D file before ordering a print from a service. The three steps, same as those described in the introduction, illustrate the printing process and double as clickable links that go to the appropriate categorical tabs. Categorical Tabs are a hierarchy of subjects relating to 3D printing, each with descriptions of what you will learn by visiting the related websites. The Related Websites (n=115) are the collected websites collected in the formative study, filtered by the selected Categorical Tab, ranging from social media tutorials to digital books. Tabs include subjects like where to obtain designs without designing, where to learn how to design, how to buy and operate printers, and where to learn about 3D printing persistently on social media. Videos are included in each tabular view, and are embedded directly into the view for convenience. The bottom has another CDQA interface, with example questions relating to the tabular categories. This includes questions that experienced practitioners may know but is not always obvious to newcomers, like "How can I make prints food-safe?" which returns comments on how to coat prints of various materials. At the end of these results, it links to the "talk" page where users are instructed on how to order or ask printing services questions.

5.4 Where to Print?: Printing with Guidance from Services

The focus of this question is *Designing-Together*, helping newcomers successfully initiate collaborations with printing services like in Berman et al. [15]. This page presents various options for printing facilities with summarized trade-offs and appropriate links to the "How to Print", where if they choose one facilitiy they are then directed to a "*talk with printing practitioners*" page. Once they have selected a facility, the page helps newcomers structure questions about what they want to print so that they may not leave out pertinent details of design-intent. The user-answers are immediately drafted into a message that can be sent to a service. Questions include information about the user, descriptions of what they want their end-product to accomplish, where the end-product will reside, descriptions of material qualities, and cost constraints. All questions are optional, but exist to help newcomers think more about their printing goals and relate them to the service.

After a message is drafted, users can edit the message as they see fit, and either email it to a local print shop or send it as a message to an online printing service. Neither commits the user to ordering a print and spending money, however cost estimates similar to the design-view are generated for these options. The email is sent from the HowDIY system to both the user email and the shop, but for online services the message is copied to the users' clipboard and then users are given instructions on how to message online printing services similar to processes observed in our survey of online services. Both proximal services as studied by Berman et al.[15] and online services as studied in the Section 4 provide human-verification and -consultation of printing ideas.

6 EVALUATION OF HOWDIY: JOINING CULTURES OF PARTICIPATION

We conducted an "*in-the-wild*" study where we recruited newcomer-users over email to utilize the system indefinitely, assessing the efficacy of the system, and providing further insight towards developing intelligent interfaces that can empower anyone to identify how they can join existing cultures of participation in 3D printing.

Procedure: To assess the efficacy of HowDIY's ability to introduce individuals to 3D printing, we conducted a study where printing-newcomers recruited from email used HowDIY for a period of two weeks. All participants had zero prior experience 3D printing in-person or through a service. All aspects of the study were conducted online. Participants were given a questionnaire before using the system, and again two weeks after. Some participants participated in an semi-structured interview after the final questionnaire, focusing on their perceptions surrounding 3D printing practices and their perception of HowDIY. The first questionnaire contained questions relating to their prior exposure with CAD and 3D Printing, demographic information, and several likert-scale measures discussed below. The followup questionnaire repeated these measures and asked short response questions relating their perception of 3D printing and relating to Olson and Olson's framework for initiating successful distance collaborations [51]. We conducted quantitative analysis of usability and of users' changing perception towards 3D printing, and qualitative analysis of newcomers' readiness to begin successful 3D printing collaborations. Participants (n=22) completed both sets of questionnaires, with backgrounds ranging from Finance to Chemical Engineering and ages from 18 to 49. HowDIY captured logs for each user's interactions on the website.

Measures: Participants completed two measures evaluating HowDIY: the System Usability Scale (**SUS**) [10] and the Creativity Support Index (**CSI**) [19] on the task of learning 3D printing. While the SUS was intended as a quick questionnaire to evaluate ease-of-use, it has been shown to be also effective at separately evaluating sub-scales of learnability and usability [45]. A grounded theory approach was utilized to analyze the qualitative interactions and questionnaire data [63], relating axial codes to themes related to Fischer and Giaccardi's three levels of meta-design.

6.1 Findings:

Overall, newcomers found the website usable, perceived it as helping them learn 3D printing, and demonstrated their greater understanding of 3D printing processes.

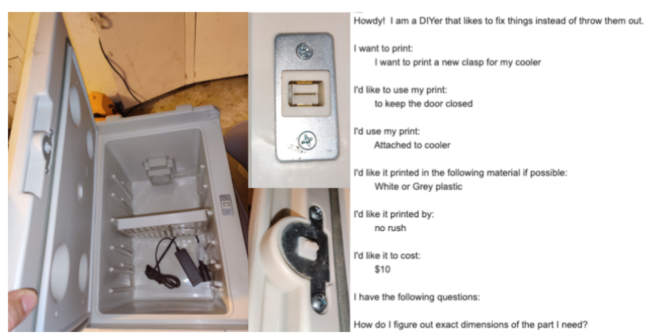

Figure 4: Specification sent by a HowDIY user to gain insight into best-practices rather than immediately fabricating and discovering potential printability flaws post-hoc.

6.1.1 *System Usability Scale.*

Overall, most users gave passing scores in the SUS and CSI (Figure 5), with the two scores being highly correlated (r=0.82, p<.0001). The SUS consists of ten likert-scale questions from 1 ("Strongly Disagree") to 5 ("Strongly Agree"), where half are questions about positive aspects of the system (5 is good) and half are questions about negative aspects of the system (5 is bad). While the end scale is represented by a single number from

0-100, these numbers are not percentages, with 68 being average and 80 being excellent [10]. While most users found the system usable (median=65), there were some users that disliked the system. Out of those who gave low SUS scores (SUS<50, n=4), all gave above-average learnability sub-scores, indicating those who didn't use the system learned how to use it faster than other users who had other complaints about usability.

Scale	Avg. Factor Counts (SD)	Avg. Factor Score (SD)	Avg. Weighted Factor Score (SD)
Exploration	3.64 (1.18)	13.30 (4.08)	49.50 (23.69)
Results Worth Effort	3.00 (1.54)	12.18 (4.81)	35.91 (22.10)
Enjoyment	2.95 (1.40)	12.23 (5.48)	36.68 (24.24)
Expressiveness	2.64 (1.29)	11.86 (5.41)	31.00 (22.49)
Immersion	2.09 (1.41)	9.50 (4.89)	21.27 (20.44)
Collaboration	0.68 (0.95)	11.23 (3.95)	7.86 (14.56)

Figure 5: CSI Counts, Scores, and Weighted Scores for each factor when learning how to 3D print with HowDIY

6.1.2 Creativity Support Index. The CSI scores revealed the factors end-users value when *learning 3D printing* and the amount of support they received along those factors when using HowDIY. The CSI requires users to evaluate which factors are needed for a given task by picking between all possible pairs of factors, then requiring the users to score each factor with two ten-point Likert scale questions. The factor counts are relative to each other, ranging from zero to six, where as one increases another must decrease. The scores range zero (bad) to twenty (good), so anything above a ten generally indicates some support of that factor in the system. The overall score is calculated by the sum of the score weighted by the counts all divided by three, resulting in the final 0-100 CSI score. The average CSI score was 60.74 (SD=22.3), above the failure threshold of 50 [19]. Below we describe each of the factors, presented in descending order based on factor count:

Exploration had the highest count and score among the factors, indicating that users value exploring different avenues for learning 3D printing which HowDIY, and felt that HowDIY facilitated this exploration. **Results Worth Effort** had a high count and value, indicating that HowDIY facilitated users' worthwhile learning about 3D printing. **Enjoyment** also had a high count and score, implying that users did not want learning to be a chore and that HowDIY was mostly satisfactory at making learning enjoyable. **Expressiveness** had a lower count and score, but still satisfactory for most, indicating that HowDIY supports this factor but that there is room for improvement in empowering users to express themselves while learning 3D printing with HowDIY. **Immersion** had a lower count and a low score, indicating that users did not forget about HowDIY while using it, but that they did not value this factor much. **Collaboration** was extremely low in count, but satisfactory for most in score. While HowDIY helped facilitate collaboration, end-users did not see collaboration as an important aspect of learning 3D printing, aligning with findings that newcomers may be hesitant to talk to stranger-practitioners when learning 3D printing [7, 37].

6.2 HowDIY as a Meta-Design Platform

HowDIY was informed by each level of the meta-design framework to broaden participation in 3D printing as a design activity involving both physical and digital media (Section 5). This section presents outcomes from the user study that align with the meta-design framework.

6.2.1 Designing Design: CAD is not Required, but Modification is Encouraged. Participants spent an average estimated 24.7 minutes on the site, split across an average of 4.8 sessions. Participants made an average of 28 searches per visit, viewing on average 5 design-views. Many visited how to remix designs seen on HowDIY. All but two participants mentioned they would be willing to print modified designs in the followup questionnaire, with the remaining two split between only printing pre-made designs or original designs they created. Most mentioned willingness to print pre-made designs (n=15), indicating that end-users recognize that CAD skills are not always required to print.

6.2.2 Designing Together: Ready to Collaborate, but Need Confidence. Most participants indicated willingness to collaborate with a printing service (n=14). Users visited the "Where to Print" page 4 times on average, but only two participants sent emails to printing services. One of those participants sent a email asking for a Thingiverse earbud holder to be fabricated, and the other asked for guidance designing and replacing a broken latch for their cooler with various images (Figure 4). Two participants printed without a service: one participated in 3D printing with co-workers, and another printed with a friend. While most showed inclination to talk with proximal services to mitigate initial costs and risks (e.g. "*[I am] worried I would somehow break something*"), one participant mentioned using online services for privacy concerns (e.g. *"The lack of human interaction would give me more freedom to print what I want without judgement!"*). Regardless of service, all were confident in their ability to begin communications with services and most would prefer to initiate collaboration by email (n=11) or in-person (n=6). However, many mentioned not contacting services or other printing facilities because they were not confident that their first print would be successful. Systems to encourage "designing together" will likely need to encourage this first contact between end-users and experienced practitioners.

6.2.3 Designing the "In-Between": Discovering an Online Shared Repertoire. Despite half of participants not knowing detailed steps of the printing process prior to utilizing HowDIY (e.g. "*I have no idea*"), all but one demonstrated detailed knowledge of printing procedures afterwards. Participants visited an average of 4 external links, finding information outside of HowDIY. Many participants mentioned that HowDIY helped them understand "*the theory behind 3D printing*" and "*demystified the process for me a bit, which increased confidence*". However, some wished for more course-like structure to learn 3D printing, something they could strictly follow to get started. While HowDIY did provide a number of YouTube tutorials, it did not provide more interactive courses (e.g. like MOOCS [62]). Those who demonstrated use of printing services through HowDIY utilized features that the studied online printing interfaces often do not support. One user did not upload a 3D file, but instead uploaded images and described his desired end-product (i.e. Figure 4), which prompted the service to respond with descriptions of various CAD tools and design-considerations for crafting his future print. This form of consultation may be supported by future meta-design systems, but cannot be supported until consultation is conducted and studied. Meta-Design platforms like HowDIY make 3D printing accessible to many less-traditional users and thus make studying these emergent interactions possible, changing the landscape of 3D printing technologies.

7 DISCUSSION: IMPLICATIONS FOR 3D PRINTING META-DESIGN SYSTEMS

In addition to continuing research directions described in Section 3, we describe additional implications for broadening participation in 3D printing practices through meta-design platforms.

7.1 Empowering Greater Expression

HowDIY only presented the most common avenues for creating 3D printing designs, not providing any explicit affordances for modification or customization of 3D geometries. The immediate next step must be providing means to modify geometries in the application, similar to metamodels as described in Section 3.1, could encourage more to print as expression. Additionally, affordances to immediately upload and modify open source designs in online CAD programs could help newcomers create novel designs and not feel as daunted by the prospect of learning CAD. This has been demonstrated by existing retailers (e.g. HeroForge [34]), who combine specification and design into a fixed menu of parameters by limiting the scope of what they will print. However, such meta-design applications should beware of opposite pitfalls in end-user development: 1) the "*Turing Tar Pit*": where everything is possible, but nothing of interest is easy, and 2) the *Inverse of the Turing Tar Pit*: where specialized operations are easy, but little of interest is possible" [25]. Another pitfall is Blikstein's *Keychain Syndrome*, where newcomers may feel incentivized to only employ a specialized application without learning other avenues of expression [16]. As a 3D file is not required to specify ideas, means to express ideas through sketches, images, gestures, and other media could encourage 3D printing online. Instead of solely designing in popular CAD programs, one could craft printable 3D geometries by scanning faces to create custom masks [1] or glasses [3], by tracing around an object in mixed-reality to create a custom stand or holder [61], or many other means of expression that do not require traditional CAD applications to support expression in a particular domain.

7.2 Printer Hardware and Software

While this work focused on how end-users may specify their ideas with printing services, which allow anyone to print from anywhere without all of the initial costs and learning-curves associated with operating printing machinery, meta-design concepts may be integrated directly into 3D printers. Printer interfaces could integrate datasets of pre-made or easily-modifiable designs, also encouraging designing while printing [40, 42]. As many are shy to seek help [7, 37, 59] and have difficulty searching online for relevant resources without guidance [15], integrating guides to social resources within consumer fabrication technologies could broaden participation beyond those who seek and engage with these communities online. Printers of the future should encourage collaboration, helping with both design of geometry and determination of printer-configurations. Sharing media relating to printer's environments and progress may lower the barrier to entry when learning printer operation [48].

7.3 Encouraging Collaborative Specification

The online printing service interface analysis revealed that many services only require the uploading of 3D files and selection of material, with optional parameters for describing design-intent. While HowDIY users did use images and text, sometimes without 3D files, many were still hesitant to begin communication with services in general. The HowDIY users CSI's indicate that collaboration was consistently the lowest priority when learning 3D printing, meaning that newcomers did not value collaboration as part of the learning process. While this collaboration count is likely influenced by socio-cultural variables that are difficult to influence, there are two pathways to further encourage newcomers' co-participation with 3D printing practitioners: **1)** provide less daunting avenues to begin communication or **2)** automate elements of print-shop communication. Broader social acceptance of printing services could help make initial contact less daunting, which could be facilitated by more socially-mediated recommendations (e.g. reviews) of printing services by third parties. Additionally, facilitating printing service interactions and deliveries in popular areas could facilitate more familiarity and curiosity towards the process. Many may be shy to begin interacting with these services, so systems that could suggest actionable warnings and errors could allow users to refine their ideas and potentially build confidence before contacting a service.

7.4 Initiating Successful Collaborations

Our social media analysis demonstrated that many learned about what can be printed through information and consultation facilitated by online services. However, in the HowDIY design probe, there were many barriers and challenges that inhibited participants from considering contacting 3D printing services. The privacy of online services was seen as advantageous. For local printing services, participants wanted to learn more about printing processes and receive guidance if stuck. Beginning communication in-person or by email were near-universally suggested by the studied newcomers for contacting printing services, but many preferred printing with the guidance of personal acquaintances when possible. The lower barrier for printing with acquaintances may be better afforded anywhere if small numbers of enthusiasts are fostered across diverse communities via formal training or online meta-design platforms similar to HowDIY, proliferating printing practices and collaborations.

8 CONCLUSION

3D printing processes require users to be knowledgable, combining many disparate technologies to successfully specify and fabricate their ideas. In this paper, we investigate how these technologies inter-relate within in a meta-design framework, supporting anyone to learn 3D printing practices. Focusing on online services that may facilitate printing anywhere, we observed that many novice end-users leverage online resources to utilize these services. While perceptions of printing price and quality were generally well-received, many online service clients expressed frustration when distinguishing flaws in digital design from flaws during fabrication. Through the development and evaluation of a design-probe HowDIY, we explored how 3D printing service platforms may better inculcate newcomers into 3D printing communities, evaluating printablility of end-users' ideas through co-participation in print specification. The design-probe demonstrated that meta-design platforms can introduce people with various backgrounds to 3D printing, revealing emergent behaviors that may otherwise be ignored. Exploring how 3D printing intelligent tools and services serve in meta-design processes and cultures of participation is key to fostering an egalitarian future of personal fabrication.

REFERENCES

[1] 2020. 3D scanning app generates customized 3D printed mask fitter. https://www.3dprintingmedia.network/3d-scanning-customized-3d-printed-mask-fitter/ Accessed: 2020-10-06.

[2] 2020. The Internet Archive Stack Exchange Data Dump. https://archive.org/download/stackexchange Accessed: 2020-07-01.

[3] 2020. Kite and Layer Team Up to Provide Customizable 3D Printed Eyewear. https://3dprint.com/228272/kite-and-layer-providing-customizable-3d-printed-eyewear/ Accessed: 2020-10-06.

[4] 2020. PushShift. https://pushshift.io/ Accessed: 2020-07-01.

[5] Celena Alcock, Nathaniel Hudson, and Parmit K Chilana. 2016. Barriers to using, customizing, and Printing 3D designs on thingiverse. In *Proceedings of the 19th International Conference on Supporting Group Work*. 195–199.

[6] Chris Anderson. 2013. Maker movement. *Wired, May* (2013).

[7] Michelle Annett, Tovi Grossman, Daniel Wigdor, and George Fitzmaurice. 2019. Exploring and understanding the role of workshop environments in personal fabrication processes. *ACM Transactions on Computer-Human Interaction (TOCHI)* 26, 2 (2019), 1–43.

[8] Mohammad E Arbabian and Michael R Wagner. 2020. The impact of 3D printing on manufacturer–retailer supply chains. *European Journal of Operational Research* (2020).

[9] Rahul Arora, Rubaiat Habib Kazi, Tovi Grossman, George Fitzmaurice, and Karan Singh. 2018. Symbiosissketch: Combining 2d & 3d sketching for designing detailed 3d objects in situ. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–15.

[10] Aaron Bangor, Philip T Kortum, and James T Miller. 2008. An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction* 24, 6 (2008), 574–594.

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

[12] Felix W Baumann and Dieter Roller. 2016. 3D Printing Process Pipeline on the Internet.. In *ZEUS*. 29–36.

[13] Alexander Berman, Elizabeth Deuermeyer, Beth Nam, Sharon Lynn Chu, and Francis Quek. 2018. Exploring the 3D printing process for young children in curriculum-aligned making in the classroom. In *Proceedings of the 17th ACM Conference on Interaction Design and Children - IDC '18*. ACM Press, New York, New York, USA, 681–686. https://doi.org/10.1145/3202185.3210799

[14] Alexander Berman and Francis Quek. 2020. ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse. *The Sixth IEEE International Conference on Multimedia Big Data* (2020).

[15] Alexander Berman, Francis Quek, Robert Woodward, Osazuwa Okundaye, and Jeeeun Kim. 2020. "Anyone Can Print": Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication. *NordiCHI 2020* (2020).

[16] Paulo Blikstein. 2013. Digital fabrication and 'making' in education: The democratization of invention. *FabLabs: Of machines, makers and inventors* 4 (2013), 1–21.

[17] Paul Ed Cairns and Anna L Cox. 2008. *Research methods for human-computer interaction*. Cambridge University Press.

[18] Toly Chen and Yu-Cheng Lin. 2017. Feasibility evaluation and optimization of a smart manufacturing system based on 3D printing: a review. *International Journal of Intelligent Systems* 32, 4 (2017), 394–413.

[19] Erin Cherry and Celine Latulipe. 2014. Quantifying the creativity support of digital tools through the creativity support index. *ACM Transactions on Computer-Human Interaction (TOCHI)* 21, 4 (2014), 1–25.

[20] Parmit K Chilana, Nathaniel Hudson, Srinjita Bhaduri, Prashant Shashikumar, and Shaun Kane. 2018. Supporting Remote Real-Time Expert Help: Opportunities and Challenges for Novice 3D Modelers. In *2018 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC)*. IEEE, 157–166.

[21] Lettie Y Conrad and Virginia M Tucker. 2019. Making it tangible: hybrid card sorting within qualitative interviews. *Journal of Documentation* (2019).

[22] Kristin N Dew, Sophie Landwehr-Sydow, Daniela K Rosner, Alex Thayer, and Martin Jonsson. 2019. Producing Printability: Articulation Work and Alignment in 3D Printing. *Human–Computer Interaction* (2019), 1–37.

[23] William Easley, Foad Hamidi, Wayne G Lutters, and Amy Hurst. 2018. Shifting expectations: Understanding youth employees' handoffs in a 3D print shop. *Proceedings of the ACM on Human-Computer Interaction* 2, CSCW (2018), 1–23.

[24] Gerhard Fischer, Daniela Fogli, and Antonio Piccinno. 2017. Revisiting and broadening the meta-design framework for end-user development. In *New perspectives in end-user development*. Springer, 61–97.

[25] Gerhard Fischer and Elisa Giaccardi. 2006. Meta-design: A framework for the future of end-user development. In *End user development*. Springer, 427–457.

[26] Gerhard Fischer and Brent Reeves. 1992. Beyond intelligent interfaces: exploring, analyzing, and creating success models of cooperative problem solving. *Applied Intelligence* 1, 4 (1992), 311–332.

[27] Gerhard Fischer and Eric Scharff. 2000. Meta-design: design for designers. In *Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques*. 396–405.

[28] Gerhard Fischer and Frank Shipman. 2011. Collaborative Design Rational and Social Creativity in Cultures of Participation. *Human Technology: An Interdisciplinary Journal on Humans in ICT Environments* (2011).

[29] Christoph M Flath, Sascha Friesike, Marco Wirth, and Frederic Thiesse. 2017. Copy, transform, combine: exploring the remix as a form of innovation. *Journal of Information Technology* 32, 4 (2017), 306–325.

[30] Joseph Fong, Margaret Ng, Irene Kwan, and Macro Tam. 2003. Effective E-learning by use of HCI and web-based workflow approach. In *International Conference on Web-Based Learning*. Springer, 271–286.

[31] Sascha Friesike, Christoph M Flath, Marco Wirth, and Frédéric Thiesse. 2019. Creativity and productivity in product design for additive manufacturing: Mechanisms and platform outcomes of remixing. *Journal of Operations Management* 65, 8 (2019), 735–752.

[32] Raul Gomez, Lluis Gomez, Jaume Gibert, and Dimosthenis Karatzas. 2018. Learning to learn from web data through deep semantic embeddings. In *Proceedings of the European Conference on Computer Vision (ECCV)*. 0–0.

[33] Albert Gordo and Diane Larlus. 2017. Beyond instance-level image retrieval: Leveraging captions to learn a global visual representation for semantic retrieval. In *Proceedings of the IEEE conference on computer vision and pattern recognition*. 6589–6598.

[34] HeroForge. 2020. HeroForge. hhttps://HeroForge.com Accessed: 2020-10-06.

[35] Eric von. Hippel. 2005. *Democratizing innovation*. MIT Press. 204 pages.

[36] Volker Hoffmann. [n.d.]. *Fachgebiet Landwirtschaftliche Kommunikations- und Beratungslehre Knowledge and Innovation Management Modul: Knowledge and Innovation Management (4301-410) Lehrveranstaltung: Knowledge and Innovation Management (4301-411)*. Technical Report. https://www.researchgate.net/profile/Anja_Christinck/publication/225616414_Farmers_and_researchers_How_can_collaborative_advantages_be_created_in_participatory_research_and_technology_development/links/00b4953a92931a6fae000000/Farmers-and-researchers-How-

[37] Nathaniel Hudson, Celena Alcock, and Parmit K Chilana. 2016. Understanding newcomers to 3D printing: Motivations, workflows, and barriers of casual makers. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 384–396.

[38] Takeo Igarashi, Satoshi Matsuoka, and Hidehiko Tanaka. 2006. Teddy: a sketching interface for 3D freeform design. In *ACM SIGGRAPH 2006 Courses*. 11–es.

[39] Marius Kaminskas and Derek Bridge. 2016. Diversity, serendipity, novelty, and coverage: a survey and empirical analysis of beyond-accuracy objectives in recommender systems. *ACM Transactions on Interactive Intelligent Systems (TiiS)* 7, 1 (2016), 1–42.

[40] Jeeeun Kim. 2017. Shall We Fabricate?: Collaborative, Bidirectional, Incremental Fabrication. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*. ACM, 83–86.

[41] Jeeeun Kim, Anhong Guo, Tom Yeh, Scott E Hudson, and Jennifer Mankoff. 2017. Understanding uncertainty in measurement and accommodating its impact in 3D modeling and printing. In *Proceedings of the 2017 Conference on Designing Interactive Systems*. ACM, 1067–1078.

[42] Jeeeun Kim, Clement Zheng, Haruki Takahashi, Mark D Gross, Daniel Ashbrook, and Tom Yeh. 2018. Compositional 3D printing: expanding & supporting workflows towards continuous fabrication. In *Proceedings of the 2nd ACM Symposium on Computational Fabrication*. ACM, 5.

[43] Harris Kyriakou, Jeffrey V Nickerson, and Gaurav Sabnis. 2017. Knowledge reuse for customization: Metamodels in an open design community for 3D printing. *arXiv preprint arXiv:1702.08072* (2017).

[44] Jean Lave and Etienne Wenger. 1991. Situated learning: Legitimate peripheral participation. *Learning in doing* (1991). https://doi.org/10.2307/2804509

[45] James R Lewis and Jeff Sauro. 2009. The factor structure of the system usability scale. In *International conference on human centered design*. Springer, 94–103.

[46] Bo Li, Yijuan Lu, Henry Johan, and Ribel Fares. 2017. Sketch-based 3D model retrieval utilizing adaptive view clustering and semantic information. *Multimedia Tools and Applications* 76, 24 (2017), 26603–26631.

[47] Yuwei Li, Xi Luo, Youyi Zheng, Pengfei Xu, and Hongbo Fu. 2017. SweepCanvas: Sketch-based 3D prototyping on an RGB-D image. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 387–399.

[48] Thomas Ludwig, Alexander Boden, and Volkmar Pipek. 2017. 3D printers as sociable technologies: taking appropriation infrastructures to the internet of things. *ACM Transactions on Computer-Human Interaction (TOCHI)* 24, 2 (2017), 1–28.

[49] Yury A Malkov and Dmitry A Yashunin. 2018. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. *IEEE transactions on pattern analysis and machine intelligence* (2018).

[50] Beth Nam, Alex Berman, Brittany Garcia, and Sharon Chu. 2019. Towards the Meaningful 3D-Printed Object: Understanding the Materiality of 3D Prints. In *International Conference on Human-Computer Interaction*. Springer, 533–552.

[51] Gary M Olson and Judith S Olson. 2000. Distance matters. *Human–computer interaction* 15, 2-3 (2000), 139–178.

[52] Thierry Rayna and Ludmila Striukova. 2016. From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change* 102 (2016), 214–224.

[53] Thierry Rayna, Ludmila Striukova, and John Darlington. 2015. Co-creation and user innovation: The role of online 3D printing platforms. *Journal of Engineering and Technology Management* 37 (2015), 90–102.

[54] Aric Rindfleisch, Alan J Malter, and Gregory J Fisher. 2019. Self-manufacturing via 3D printing: Implications for retailing thought and practice. *Marketing in a Digital World (Review of Marketing Research* 16 (2019), 167–188.

[55] Horst Rittel. 1984. Second-generation design methods. *Developments in design methodology* (1984), 317–327.

[56] Xin Rong. 2016. *word2vec Parameter Learning Explained.* Technical Report. http://bit.ly/wevi-online.

[57] Victor Sanh, Lysandre Debut, Julien Chaumond, and Thomas Wolf. 2019. DistilBERT, a distilled version of BERT: smaller, faster, cheaper and lighter. *arXiv preprint arXiv:1910.01108* (2019).

[58] André C Santos, Luís D Pedrosa, Martijn Kuipers, and Rui M Rocha. 2012. Resource description language: A unified description language for network embedded resources. *International Journal of Distributed Sensor Networks* 8, 8 (2012), 860864.

[59] Jessi Stark, Fraser Anderson, George Fitzmaurice, and Sowmya Somanath. 2020. MakeAware: Designing to Support Situation Awareness in Makerspaces. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 1005–1016.

[60] Nikolai Stein, Benedikt Walter, and Christoph Flath. 2019. Towards Open Production: Designing a marketplace for 3D-printing capacities. (2019).

[61] Evgeny Stemasov, Tobias Wagner, Jan Gugenheimer, and Enrico Rukzio. 2020. Mix&Match: Towards Omitting Modelling Through In-situ Remixing of Model Repository Artifacts in Mixed Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[62] Christian M Stracke, Stephen Downes, Grainne Conole, Daniel Burgos, Fabio Nascimbeni, et al. 2019. Are MOOCs open educational resources?: A literature review on history, definitions and typologies of OER and MOOCs. *Open Praxis* 11, 4 (2019), 331.

[63] A Strauss and J Corbin. 1990. *Basics of qualitative research*. https://genderopen-develop.cms.hu-berlin.de/bitstream/handle/25595/12/whatsnew7.pdf?sequence=1

[64] Zuk Turbovich, Amarendra K Das, Iko Avital, Gedalya Mazor, et al. 2016. Personal 3D-Printing: A Remapping of the Relationship between Product Designers, Products and Users. *DS 85-2: Proceedings of NordDesign 2016, Volume 2, Trondheim, Norway, 10th-12th August 2016* (2016), 012–021.

[65] Christian Voigt. [n.d.]. Not Every Remix is an Innovation: A Network Perspective on the 3D-Printing Community. ([n. d.]). https://doi.org/10.1145/3201064.3201070

[66] Linlong Xiao, Nanzhi Wang, and Guocai Yang. 2018. A reading comprehension style question answering model based on attention mechanism. In *2018 IEEE 29th International Conference on Application-specific Systems, Architectures and Processors (ASAP)*. IEEE, 1–4.

[67] Di Yang, Aftab Hussain, and Cristina Videira Lopes. 2016. From query to usable code: an analysis of stack overflow code snippets. In *2016 IEEE/ACM 13th Working Conference on Mining Software Repositories (MSR)*. IEEE, 391–401.

[68] Tom Yeh and Jeeeun Kim. 2018. CraftML: 3D Modeling is Web Programming. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 527.