Digital Fabrication Tools at Work: Probing Professionals' Current Needs and Desired Futures

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ABSTRACT

Digital fabrication tools have transformed how people work in micro- and small-scale manufacturing settings. While increasing efficiency and precision, these tools raise concerns around user agency and control. This paper describes an exploratory study investigating the felt work experience and desired futures of professionals who use fabrication tools. We conducted co-design workshops with 23 professionals who use 3D printers, laser cutters, and CNC routers. We probed about current practices; machine awareness and autonomy; and user agency. Our findings reveal that current tools are not very professional. They are unreliable and untrustworthy. Participants desired smarter tools that can actively prevent errors and perform self-calibration and self-maintenance. They had few concerns that more intelligence would impact agency. They desired tools that could negotiate trade-offs between time, cost, and quality; and that can operate as super-human shop assistants. We discuss the implications of these findings as opportunities for research that can improve professionals' work experience.

Author Keywords

digital fabrication; CNC; laser cutting; 3D printing; intelligent systems; user experience; co-design; future of work

CCS Concepts

•**Human-centered computing** → *User studies*; Participatory design; •**Applied computing** → *Computer-aided manufacturing*;

INTRODUCTION

Digital fabrication tools (DFTs, e.g., 3D printers, laser cutters, CNC machines) have transformed small-scale manufacturing and impacted the practices of professional craftspeople. These tools allow for greater precision, control, and reproducibility when shaping materials. DFTs are of growing interest within the HCI community [31, 29], with work focused on making the tools easier to use, hacking the tools to extend their capabilities, and studies of how this technology has impacted people, including issues of agency and creativity.

Tools like table saws, band saws, and hot-wire cutters require users to handle the material during a shaping process, helping to create tacit knowledge of the material and adding to a felt experience of making a thing. With the arrival of DFTs, there has been some concern about a loss of agency, craft skill, creativity, and pleasure in making [9, 4]. Research has attempted to address this by developing intelligent DFTs that enable people to directly control and manipulate the tool [50].

To investigate possible futures for machine autonomy and its impact on user agency and control, we asked, “What would happen if DFTs gained more intelligence: sensing, actuation, and reasoning capabilities? How would users feel if these machines became smarter to the point of being an active collaborator in the making of things? Would this be good?” We chose to ask these questions in order to surface insights on how these machines might become more intelligent and capable in ways that do not negatively impact the human experience.

We sought answers to these questions through co-design workshops with professionals who regularly use DFTs as a core part of their work (e.g., custom manufacturers, entrepreneurs, and fabrication specialists). We asked them to share stories of their current experiences and to speculate on what a collaborating DFT might be. Participants shared many insights on their current struggles and on desires for preferred futures. Most had experienced several catastrophic failures. They did not trust current DFTs. They had few concerns that smarter tools would impact their agency and feelings of control. They specifically desired smarter tools that would prevent errors and perform self-calibration and self-maintenance. In terms of collaboration, they wanted intelligent tools to behave as shop assistants rather than collaborators. They desired more self-aware tools that could effectively negotiate trade-offs between time, cost, and quality. Finally, they shared many requests for advanced features that could help improve their skills and that would more broadly support the entire fabrication process.

This study makes two contributions. First, it offers a description of the felt work experience of professionals, an important group not well studied in prior work. Second, this work helps broaden understanding of boundaries between machine autonomy and human agency in the context of fabrication to inform the development of future intelligent tools.

RELATED WORK

Below we situate our research with respect to prior work, noting where we extend the ideas of others and where we

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break new ground. We provide an overview of how HCI has made technical advances to fabrication systems and work describing the broader impact of this emerging technology.

Advancing Fabrication Systems

Researchers, hobbyists, and businesses have all worked to advance the software and hardware that drives digital fabrication systems. Much research focuses on extending the capabilities of DFTs to enable new workflows, novel interactions, and fabrication with new materials [20, 35, 36]. Researchers and the maker community have developed open-source hardware and software; some of these are design interventions, such as hacks for error detection [3, 42, 16, 17], whereas some are additions that bring new functionality, such as enabling remote control and monitoring of devices [33]. HCI researchers have also investigated how DFTs can become more accessible to a larger audience. Studies include design tools and hardware developed to make using DFTs easier by enabling new workflows that assist non-expert users with domain-specific knowledge [39, 21, 23]. Some researchers have addressed fabrication speed by exploring low-fidelity fabrication for faster design iteration [30]. And, of course, manufacturers use new features to drive sales and adoption [8, 13]. All these efforts aim to enable users to achieve more by improving or expanding the capabilities of fabrication systems.

A related strand of research looks at how to develop digital fabrication tools with a focus on user agency. With the transition from traditional to digital tools in making, researchers have raised issues around computational agency and control with concerns of loss of human engagement and decision making [28, 50, 7]. Interactive Fabrication was one of the paradigms that was proposed to address these concerns by enabling direct manipulation in DFTs [46]. Several studies embracing this hybrid approach explored how DFTs could be more collaborative to improve the felt experience of making [49, 32, 37, 12, 2]. The vision in these instances was about augmenting human capabilities by leveraging machine autonomy and intelligence, instead of automating away people's agency. But despite all the concerns around user agency in digital fabrication, very little empirical research has investigated where and how users feel a loss of agency and control in digital fabrication [6]. More research is needed to understand which aspects of making are critical for users' agency, and which aspects can be delegated to machines.

Broader Impact of Fabrication Technologies

HCI research has investigated the implications of digital fabrication as a socio-technological phenomenon and its impact on the way people work. Most studies have focused on the maker movement and explored various contexts in which people practiced making [45]. It is important to note that "makers" – users of DFTs – are not a homogeneous group; there are different types of makers including professionals, hobbyists, researchers, novices, casual makers, and industrial workers [14]. Research most often investigated the user experience of non-professionals to understand the barriers to using DFTs [41, 19, 24, 43]. Little HCI research has investigated the user experience of DFTs in professional settings.

Figure 1. One of our co-design sessions. We held our sessions in spaces where DFTs were available for participants to reference during activities.

The few works that have explored how professionals use DFTs include studies that investigated the challenges of using 3D printers in a university lab setting [26], and the challenges industrial workers face with DFTs in factories [47]. In addition, some researchers have explored the intersection of hobbyist and professional making [25]. Recently, workshops at CHI and similar venues addressed this as a gap for future HCI research to bridge [11, 10, 15]. Our study is focused on professionals in micro- and small-scale settings, a group that has overlaps between personal and industrial production.

Our work attempts to bring these strands of related work together. We build on the idea of advancing machine intelligence in DFTs with an eye on where and how these systems could support users in their work.

METHOD

We wanted to probe the idea of making DFTs more capable, of increasing their sensing and actuation capabilities so they might function more as an active collaborator and less as a dumb tool. Would more intelligent machines negatively impact users' sense of agency or would this intelligence be appreciated? We wanted to explore the boundaries between human agency and machine autonomy in the context of DFTs.

We chose to focus on professionals who use DFTs as a core part of their work for several reasons. First, professionals have expertise and considerable agency in how they perform their work. They seemed a good choice for probing on the open issue of autonomy and agency. Second, professionals have been central in the development of design theory on reflective practice [40], again making them an interesting group to explore the intersection of creative practice, control, and machine intelligence. Third, professionals are critical stakeholders; tool and device manufacturers cater to their needs when adding new options and capabilities. Finally, we liked professionals because they have been less investigated than other communities with respect to DFTs.

As a first step, we conducted a pilot field study, speaking with 16 people who both use and work at a variety of maker spaces. These interactions helped us resolve our focus on the tension between machine autonomy and human agency. It also informed our choice to focus on professionals. One clear

distinction that emerged was that for many hobbyists, making was a lot about improving their own expertise with DFTs. For professionals, the end product seemed to play a larger role, though they also cared about growing their own expertise and about the felt experience of working. Our time spent in maker spaces and interviewing makers led us to focus on people who use three different DFTs: 3D printers, laser cutters, and CNC routers. Parallel to the interviews, we read research about DFTs, user experience around fabrication systems, and human-robot collaboration. The combination of the literature, the interviews, and our time spent hanging out in maker spaces led us to focus on asking if DFTs should be collaborators.

Due to the exploratory and probing nature of our research questions, we chose to hold co-design workshops. Co-design differs from other user-centered methods in that it asks participants to actively participate in envisioning the future they desire [38] instead of focusing on breakdowns in current processes [18]. Experts in co-design point to three types of activities: tell, make, and enact [5]. *Tell* activities scaffold participants in telling stories of current experiences. *Make* activities ask participants to envision new ways of working in their future. *Enact* activities direct participants to act out future practices and to reflect on the implications of this future. Our workshops used both *tell* and *make* activities.

To recruit, we reached out to local maker spaces, university shops, and small-scale, customer manufacturers, such as companies that make custom kitchen cabinets. We used snowball sampling, asking our participants to recommend other professionals they knew of who regularly used DFTs.

We conducted six co-design workshops, each with 3-4 participants (Figure 1). These took place in different locations including local maker spaces, a small-scale manufacturer of office, and a university fabrication shop. We chose locations that allowed access to DFTs in order to aid participants in recalling and reflecting on their current experiences and desires for the future. Workshops lasted 2 hours. The first 10 minutes allowed everyone to get acquainted. We then led them through two different constructive activities that each took 50 minutes. The final 10 minutes allowed for a wrap up where we answered any final questions. Participants were paid 20 USD.

The first co-design activity (tell) asked participants to share their current experiences with DFTs. We prompted them to share a story about a time where they got frustrated with digital fabrication tools, and to tell a story about when they felt they had superpowers as a maker and accomplished as a professional. For the second activity (make), we asked participants to envision future interactions with DFTs. Participants brainstormed ideas using worksheets with prompts such as “a \$5 idea” or “a \$5 billion idea”. Each participant presented their solutions and explained why they were important. Throughout the sessions, we explored the boundaries between machine autonomy and user agency by using probes such as “*if your tool was intelligent enough to do anything, which part would you keep to yourself in the process of making?*”

We analyzed our data by using affinity diagrams to perform thematic analysis. Traditionally, most qualitative HCI research

has used grounded theory for analysis. We broke from this tradition as our focus was much more on understanding preferred futures than on building a detailed theory of the present. Affinity diagramming has been used effectively in design practice, where the focus is on the construction of a preferred future, and we observed that recent HCI qualitative work with a future focus has increasingly used this analysis approach [34, 27, 48]. We audio-recorded all of the workshops and generated transcripts. We reviewed these as well as the artifacts participants created, drawing out insights and observations into individual notes. These were iteratively rearranged based on their affinity to one another. This produced 21 clusters from which we constructed four main themes.

FINDINGS

We organized our findings around four main themes: Professional Practice, Unprofessional Tools, Machine Autonomy and Human Agency, and Negotiation of Trade-offs. Below, we first provide some details on our participants’ backgrounds and experiences. We then describe the four themes from our analysis.

We recruited 23 participants (Table 1). All had at least three years of experience working with DFTs, with a median of nine years of experience. Most had experience with 3D printing, laser cutting, and use of a CNC router. They had experience with a variety of materials including wood, paper, plastic, ceramic, fabric, metal, and stone. 3D printers used by our participants cost 700-4000 USD, and included products from MakerBot, Prusa, and FormLabs. Laser cutters cost 5-28K USD, and included products from Rabbit, Trotec, and Universal Laser Systems. CNC systems cost 15-30K USD and included machines from ShopBot and CNT Motion Systems. Overall, the fabrication systems that our participants had access to involved low to mid-range tools. It is important to note that higher-end DFTs with increased automation capabilities exist for medium- and large-scale manufacturers. This is out of the study scope, as our focus was on micro- and small-scale manufacturers.

Participants had a wide range of professional backgrounds. Based on their work, we placed each into one of four categories: custom manufacturers, shop stewards, entrepreneurs, and fabrication specialists:

- Custom manufacturers: Craftspeople, designers, and contractors engaged in design, fabrication, and delivery of low volume and one-off custom products.
- Shop stewards: Shop managers and assistant managers for shops and maker spaces. Helped people to effectively use DFTs and maintained these machines.
- Entrepreneurs: Fabricators and engineers working for startups that produce novel material goods as a core part of their business.
- Fabrication specialists: Designers and engineers working at established companies to create new designs. They would prototype with DFTs to validate their designs.

As professionals who interact with DFTs as a critical component of their work, participants described their work across

Session	ID	Professional Role	Exp.	Gn.	Session	ID	Professional Role	Exp.	Gn.
1	P1	Custom Manufacturer	20 yrs	M	4	P13	Entrepreneur	6 yrs	M
1	P2	Shop Steward	23 yrs	M	4	P14	Shop Steward	6 yrs	M
1	P3	Shop Steward	30 yrs	M	4	P15	Shop Steward	6 yrs	M
1	P4	Shop Steward	9 yrs	M	5	P16	Custom Manufacturer	10 yrs	M
2	P5	Custom Manufacturer	30 yrs	M	5	P17	Entrepreneur	7 yrs	F
2	P6	Custom Manufacturer	15 yrs	M	5	P18	Custom Manufacturer	5 yrs	M
2	P7	Shop Steward	3 yrs	M	5	P19	Custom Manufacturer	18 yrs	M
2	P8	Entrepreneur	15 yrs	M	6	P20	Custom Manufacturer	3 yrs	M
3	P9	Fabrication Specialist	8 yrs	M	6	P21	Custom Manufacturer	24 yrs	M
3	P10	Fabrication Specialist	6 yrs	M	6	P22	Custom Manufacturer	3 yrs	F
3	P11	Fabrication Specialist	4 yrs	M	6	P23	Custom Manufacturer	11 yrs	M
3	P12	Fabrication Specialist	10 yrs	M					

Table 1. Overview of study participants.

three phases: design, fabrication, and finishing. Their responsibilities included managing settings for both design software and DFT software; acquiring and quality control checks of material; maintenance of DFTs; managing software updates and conflicts; maintaining safe and healthy fabrication environments; operating design software and DFTs; and tracking the performance and quality of their tools and overall work.

Professional Practice

One emergent theme was participants' professional practice. They cared about "being a professional". We identified three major areas where this really seemed to matter: (1) resource management, (2) quality under uncertainty, and (3) creative utilization of DFTs.

Resource Management

Participants cared about effectively managing resources, such as time, money, materials, and equipment. How they allocated these resources differed based on the nature of their practice and particular situations. Their strategies included optimizing their time and output based on an hourly income, as well as minimizing the costs of operations to keep DFTs accessible. Regardless of the strategies they employed, they spoke of the allocation of resources as critical to how they created value. For example, P3, when discussing how he manages his shop stated, *"You need to have some idea about the number of types of machines that you'll need to work with, a certain range of materials, and a general idea about what things cost, and how long things take. And you need to know what your limitations are going to be."*

P16 was even more explicit in connecting resource management to value in terms of revenue per hour of effort. *"I design and fabricate a lot of stuff for Etsy, and I need to make a certain profit when I'm doing that. I want to make 60 dollars per hour, so I calculated the price of my Etsy items based on how long it takes me to make that."*

P2 spoke of a more general strategy related to selection of materials. He invested effort to choose the cheapest materials, but he also required that these be high-quality materials. As

a professional, he had the ability to discriminate their quality beyond sale price.

DFTs were viewed as a resource measured in terms of time. This includes their availability (not busy with another project) and the amount of time they could or could not be operating because of maintenance. Professionals worked to efficiently schedule multiple jobs that needed a single DFT, and they worked to break up jobs that could be spread across multiple DFTs. P6 spoke of this when discussing the potential advantage of upgrading his current setup. *"If we had a network connected to the laser, one person's job could be running while the other person is setting up. And there would be a lot more time where the laser could be actually on and running."*

Quality Under Uncertainty

Professionals had to handle the uncertainty that the real world imposes. They had to be able to work with imperfect tools and materials to create physical products that consistently met target qualities or specifications. As P3 put it, the end products needed to *"work"* while they also looked *"nice and consistent, and not warped, distorted or burnt through."*

For some participants, ensuring quality was necessary to achieve engineering performance. P17 spoke of the precision level she needed in her product parts. *"I gotta make 20 of these and I need to be exactly perfect so when I test them I know how it fails."* Some participants also viewed quality as a mark of craftsmanship. P1 shared his pride in making tight fitting joints, producing high quality furniture that he imagines will outlive him. *"Somebody 300 years from now will still enjoy this piece because of the way it's made."*

Achieving quality with current DFTs was not an easy task. Participants had to be aware of tolerances, calibration, vibration, and material properties to obtain precision. A major challenge participants had to overcome was the inconsistency in materials. P18 spoke of the breadth of variation in sheet materials when describing these difficulties: *"There's always low spots, less than 1/16 of an inch, but the whole material fluctuates very slightly."* Participants implicitly expressed a

desire for more consistency in the materials and adaptability in the tools faced with working on inconsistent materials.

Creative Utilization of DFTs

The ability to use DFTs in creative ways seemed to be core to participants' work as a professional. They enjoyed and took pride in coming up with personal solutions. This sentiment was most strongly shared in how they integrated DFTs to complete projects and how they would customize their DFTs.

Participants shared that their extensive experience with DFTs led them to develop a sense for how to best use these tools for particular tasks. This involved selecting a course of actions to achieve a desired result (e.g., an etching pass followed by a cut operation on laser cutter). P3 described this process as unique to each practitioner. *"If you say 'make this cube', everyone will do it in their own way."* He explained that having no single "right way" to do something allowed them to be creative in the way they use DFTs in their work.

P5 spoke of the importance of "knowing a lot of ways" as part of their expertise. *"The key is knowing that there's a better or different way of doing something. If I know about ten different ways to work, then I wouldn't be stuck doing it a certain way."* He described the ability of being conversant with a larger set of tools as a definitive aspect that shapes professionals' creative vocabulary.

Creativity in utilizing tools was not limited to working with a single DFT. Participants most often combined several DFTs along with conventional shop tools (e.g., table saw, sander) in their processes. This orchestration was an essential part of their agency and creative decision making. P20 described how he switched between a CNC router, laser cutter, and sander to achieve his tight-fitting multi-piece ornament designs. He was able to translate his designs between devices by taking an extra step to ensure alignment across DFTs.

Participants often spoke about how they customized and fine tuned DFT settings and operations when discussing the designs and artifacts they produced. Part of their expertise seemed to stem from their ability to tweak these tools and settings in unconventional ways to achieve extraordinary results. For example, P23, when discussing how they get a smooth edge with laser cutter stated, *"There's a big difference between cutting it and throwing flames at it. You can do it elegantly to get that nice, clean edge."* He spoke with pride when describing how their studio fine-tuned settings to achieve cuts that even seasoned craftspeople could not tell were made on a laser cutter. *"We're always trying to find ways to make it not look like laser work, because the laser is cool but no one wants it to look like a trick."* Through customization, they were able to produce pieces that explicitly demonstrated the mastery they had in their craft.

All participants emphasized that "the best settings" are situation- and person-dependent. P11 spoke of this when describing the custom jig he built to etch glass objects. *"Our results I thought came out perfect, and other people might have thought their results came out perfect. It's about what you want."* Participants learned to tailor DFTs to achieve what "works best" for their process through years of practice. As

a result, they were extremely skillful in experimenting and pushing the limits of DFTs.

Unprofessional Tools

Participants did not trust DFTs to perform well. The tools were unsafe, they were unreliable, and they required (but did not always get) constant supervision when they "automated" the work of adding or removing material.

All participants had experienced major catastrophes when using DFTs. Most had experienced a tool catching itself on fire with no awareness that something had gone wrong. These machine-on-fire stories came up in every session. P12 spoke with great frustration about 3D printers and their lack of self-awareness. *"...they can catch fire and stuff like that. [It would be great to] have some type of safety thing that if it did catch fire, it could actually help itself."* P9 spoke about the danger of complacency and trust. *"I wasn't that scared before. I was like, I'll just put it in one corner, and it will work. But when I caught the printer [about to catch fire] I was like, this is a disaster waiting to happen."* He modified his shop by installing a smoke alarm above the printer, and he spoke of a desire to attach this to an automated fire suppression system.

Participants felt DFTs should be continually monitored while running, though they often chose to walk away from a running tool. Most participants shared stories of DFTs either taking unexpected actions or failing to take specified actions, resulting in poor quality or ruined work. In describing his use of a laser cutter to make a wooden tool organizer, P16 spoke of the unpredictability of the outcome: *"Did it really cut it? Am I gonna pick this up and have a finished piece or am I gonna pick this up and have some wood split because there's a pocket of glue?"* The lack of trust in the tools even soured some participants' work experience for the time they had to spend using these tools. *"I hate machining, I don't like it. It gives me a lot of anxiety to sit and wait for a CNC to ruin the thing that I just spent 50 bucks creating."* (P17)

Participants experienced these issues daily. The mathematical perfection of software would break down in the translation to real materials and tools. This negatively influenced their experience with DFTs and decreased their ability to perform as professionals. Participants described several coping mechanisms, including running an operation before cutting or printing material to preview the action of the tool (P1, P17); keeping religious journals and checklists of settings (P4); and being careful about getting specific materials from the same sources (P3, P12).

Participants were not happy with the performance of current DFTs. However, they seemed conflicted around the idea of more intelligence as a way to address these problems. Some worried that "smart" features meant to increase reliability might make things worse. For example, when discussing intelligent tools, P17 and P19 shared their frustration with a smart 3D printing extruder which constantly reported that it was jammed while it wasn't. P19 further explained his skepticism, *"Sometimes they try to make it smarter but then they get sensor glitches which makes it worse."*

Their current experiences seemed to negatively influence their confidence that DFT manufacturers could make things better. In part, some worried that sometimes manufacturers would use these against them. P4 shared his disappointment with chipped 3D printing spools which indicate their status as empty and prompt users to change spool. *“You crack it open to find out that it’s actually half full, then you have voided your purchase on that one. And the supplier won’t replace it.”* Some participants also expressed concern that smarter tools might make them overly reliant or complacent. P3 spoke of how overtrust in DFTs led them to slip back into comfort, which resulted in more failures. *“We get complacent because we constantly are told to assume that technology is taking care of it. ... you get this automatic dangerous trust, just drives into a hole of ‘it will be fine’.”*

Machine Autonomy and Human Agency

We probed participants about working with more intelligent DFTs that can easily take over tasks to support their work. Their responses revealed several insights into the boundaries between machine autonomy and human agency. In general, we were quite surprised by their desire for more automation and their general lack of concern for lost agency. However, the areas where they asked for the most automation did not seem critical to their experience of agency in their work. Nearly everyone asked for smarter tools that could prevent errors, perform self-maintenance, and perform self-calibration. Automating these was generally viewed as giving them back precious time which they could use for more important aspects of their work:

“From a business standpoint, the less I have to do personally the more money I make. On my own personal projects, I’d still rather just push a button and have the part come out. Cause I could be making something cooler, using my brain rather than sitting watching some machine.” (P19)

Participants desired automation in two major ways: they wanted DFTs to (1) take over mundane tasks, and (2) leverage their inhuman capabilities, such as a perfect computational memory and an immunity to boredom and fatigue, to enhance the professional’s fabrication experience.

Awareness for Automation of Mundane Tasks

Participants valued automated DFTs that could pick up menial work, such as setting up machines, registering and aligning materials, and calibrating tools. Most participants found such tasks prone to human error and therefore better suited to machines.

Participants desired DFTs with more self-awareness. Almost all used the phrase *“because the machine doesn’t know...”* when complaining about current DFTs. For example, they wanted tools that could monitor themselves for faults, like clogged nozzles (3D printer), broken bits (CNC router), or fires. They also wanted DFTs to be able to tell the types of end-effectors that are loaded, such as the bit size or the nozzle diameter. Participants shared that automating these tasks would save time and prevent errors.

Participants also desired DFTs that have better awareness over the DFT’s physical workspace. They shared a desire for tools

that can avoid running into themselves, the workpiece, objects, and the user. Several participants shared their frustration with CNC routers crashing into clamps. P16 further stated that DFTs should be able to suggest where to put the clamps in the first place. *“It could say ‘that’s a lousy place to put a clamp, why don’t you put a clamp over there?’”* P8 spoke of the ability to locate and self-register materials as these were among the most time consuming tasks. For participants that combined different DFTs in their processes, awareness over workpiece placement was extremely valuable as it would allow them to work with the same material across multiple devices. *“You need to be able to move between the CNC and laser [cutter] and numerically load your material to the same spot.”* (P21)

In addition to workspace awareness, participants desired DFTs to have awareness of material types. They wanted DFTs to identify the materials they were working with, so that the system could check settings for errors, record settings for each material, and suggest settings based on material. Some participants indicated that it would be helpful if DFTs could sense material properties. A large number of participants wanted DFTs to account for physical qualities and irregularities in materials (e.g. knots, material grain) so that users can be mindful of these while fabricating. For example, P23 desired a laser cutter that could identify knots in wood and go over them twice to ensure cuts.

The major ability participants wanted DFTs to have was an awareness over self-performance: tools that are aware of their own actions and the results of those. They envisioned future DFTs to validate the results of their actions in real time, and take action if there is a problem. As P16 put it, DFTs should have *“the ability to say, this is what the part should look like when I’m done.”* This notion of a feedback loop came up in every session. Some participants expected DFTs to self-adapt and automatically recover upon detecting errors, whereas others wanted the system to get approval before execution – without interrupting the flow of work: *“It could say ‘I think you’re gonna run into the clamps, I’m gonna raise the part, do an air pass on this next block and then go back to where we were’, and then I can approve it without having to stop the machine.”* (P17)

Most participants favored the idea of DFTs that self-adapted their settings based on the result of operations. However, they were cautious about fully automated systems. Most participants imagined future DFTs to provide suggestions on the operations and settings they utilized, yet they desired to maintain their agency over the decision making process. Referring to such a system as a *‘consultant’*, P4 emphasized that he wanted to be involved the design process to be able to say *“I do like these aspects ... now I’m gonna bring them into a different way of making that none of us came up with initially.”*

Participants’ concerns often centered on the inability to customize DFTs. They desired the convenience of automated systems, yet all wanted to remain in control when needed. Discussions surfaced participants’ worries about losing the ability to customize DFTs or to use them in unconventional ways that tools were not designed for. P7 described this when

discussing intelligent tools. *“I would be fine with everything being automated if I had the ability to go back and tweak it. If you didn’t like it, you should be able to take manual control over it.”*

Some participants described a spectrum that ranged from automatic to manual where they would have base settings, yet they would be able to ask for a greater level of control and experiment as needed. However, they were wary of automated systems that dictated a certain style of use. P12 described his experience with an ‘easy to use’ consumer grade desktop laser cutter. He desperately tried to cut and etch using a vector based file, whereas the software asked for a bitmap file, and then only allowed etching with that file format. He stated that he felt limited by the tool: *“I didn’t understand how to use it. ... I was like, no, this isn’t the way it’s supposed to work!”*

Leveraging Machine Capabilities

Participants envisioned future DFTs that could improve their current workflow by leveraging new machine capabilities. They desired systems that have personal and collective awareness for additional support throughout the whole process.

Participants described future DFTs that have high awareness of personal use. They wanted systems to have the ability to log and recall settings, time, and materials, as well as the end product. P23 spoke of documentation and on demand personal analytics as essential for self-reflection. *“I can go like, ‘Oh that sheet was this, it took X amount of time, and the settings were this’. Now I can reference that.”*

In addition, participants wanted DFTs to keep track of their parts over time for providing maintenance and error diagnosis support. Several participants described a DFT that could alert users on when to replace parts in advance. P7 shared that this would be even more helpful for shared devices in maker spaces. *“When you start having 30 machines, it’s hard to keep track: I replaced a bearing last week, but what machine was it?”* Some participants asked for DFTs that could compensate power settings based on this awareness over the wear in parts. P2 described two laser cutters in his fabrication shop, one of which had a new laser tube that was recently replaced. He stated: *“They don’t do cuts with the same settings, you have to learn how to back it off. It would be crazy if it could self-adjust the cut based on wear over time.”*

All participants desired DFTs to have awareness of whether the results worked or not. They wanted to be able to customize these results based on their preferences to train the system, and say *“this is what I consider a good cut, because I use this laser totally different from everyone else”* (P23). They also wanted DFTs to learn these patterns over time to provide personalized suggestions, such as *“you wanna use the same settings you used the last time for birch wood?”* (P12)

Most participants envisioned future DFTs to have awareness beyond personal use. They desired collective awareness that would come from multiple users’ results. Participants wanted DFTs to make sense of this data to enable the discovery of new settings, for example by suggesting *“George in Oklahoma did this with that, and it worked great!”* (P21). P3 and P4 described these as a way to learn several different ways of

doing things. However, several participants pointed out that the system should present an indication of the credibility of these user-generated suggestions.

Some participants were interested in the idea of DFTs with collective awareness for collective improvement. P8 deliberated on this when discussing how systems can learn from data. *“When you figure out what’s wrong, you could actually capture those events, identify when they happen and what trends trigger those events to happen”*.

Participants also wanted DFTs to leverage physical capabilities in novel ways. Their responses revealed that current DFTs provide little support for post-processes, an aspect of the work most viewed as both tedious and critical. Several participants expressed a desire for DFTs that support smoothing processes including finishing and sanding. P21 pointed out to the practicality of being able to sand with a CNC router that already has a registered piece of material and toolpath showing where it had been cut and needed smoothing. This same information could also help with the application of coatings such as primer or stain. In addition, participants wanted DFTs to have inspection capabilities for assessing quality and accuracy. This type of awareness could improve initial cuts, leading to cleaner joints and improved surfaces, thus reducing efforts needed for post-processes.

Interestingly, the way participants described future DFTs resembled an intelligent tool that works like a shop assistant, rather than a collaborator. P19 described his idea of an intelligent DFT as if it was an employee in his shop. *“[I would] have it do what you can pay somebody minimum wage for.”* Similarly, P23 likened the intelligent DFT to a helper. *“I often fantasize about having someone following me around, photographing my work and writing things down.”* He stated that the tool can pick up these tasks to help him remember settings, time spent and materials used.

Negotiation of Trade-offs

Participants’ narratives revealed that professional users needed to make trade-offs between time, quality, and cost as part of their practice. This was an important aspect for their work as it required them to coordinate all major skills: managing resources, achieving quality under uncertainty, and exerting creative agency. Most participants shared that they struggled while making these trade-offs.

One of the reasons for their struggle was that they did not always know the level of quality they needed. P11 spoke of this when discussing how 3D printers could help in making trade-offs. *“...[system could say] ‘Do you realize that at this level you’re getting this quality, do you need that quality? You can have this or that.’ Or, ‘Are you okay with it being a little lighter, I can save you 5 minutes and get you out of the shop earlier’...”* P8 pointed out that even if he knew the degree of quality needed, it was still difficult to navigate the settings. He found the current software interfaces obscure, and stated that current systems offer little support. *“[If I wanted to make something] like a doorknob, and I want it to be smooth and shiny. What are the settings for that, I don’t know. [For] a lot of that [surface finish], there’s not much support.”*

Participants shared that they would value DFTs that had more awareness over the workpiece so that they could effectively negotiate trade-offs between time, cost, and quality. They described their preferred interactions in a way that involved DFTs in this decision making process. P23 spoke of how large gains in cost might affect his design decisions. He wanted DFTs to have awareness over material properties, so that they can negotiate based on such constraints. *“For some of my things, I don’t want to cut them off the [wood] grain direction. ... But if it says ‘It looks like I could fit 72 of these instead of 36 you got packed, do you mind grain going in different direction?’, I would probably be like, hell yeah!”*

P20 desired the ability to make quality trade-offs based on the importance of pieces. *“Each of the pieces can have a grain determination, maybe these stars could be cut this way or the other way, and that’s it. Maybe other cuts are less important, cut it wherever you want.”* He stated that this would enable him to prioritize efficiency or quality where needed, while working on the same piece of material.

DISCUSSION

DFTs have a direct impact on the felt work experience of professionals in micro- and small-scale manufacturing settings. These tools are necessary for productivity. Mastery of them could be a source of pride, but more often the tools were viewed as a source of frustration. Prior work identified tensions between machine autonomy and user agency [50, 6], which also comes into play when considering intelligent tools.

Our findings suggest several substantial opportunities for future HCI research in this area. We found that DFTs need more awareness in order to perform as professional tools; that they should behave as assistants, rather than collaborators; that DFTs’ interfaces should highlight, and help their users negotiate the trade-offs inherent to fabrication; and that, collectively, these innovations would support professionals in their roles without threatening their agency.

We present these design implications in Table 2, prioritized by potential difficulty and value. We categorize the feasibility of each design intervention based on the anticipated effort and whether similar technologies exist, and value by the number of participants interested in the idea.

Towards Professional DFTs

Our findings demonstrate that DFTs fail to perform as professional tools. The inability of these systems to perform as safe and reliable work tools has led to a significant decrease in professionals’ performance and satisfaction in using DFTs. One of the major abilities that characterized professionals’ practice was their expertise in achieving quality under uncertainties, such as material inconsistency. Our study indicates that DFTs add to this challenge by their unreliable behavior. Previous work has pointed to the lack of trust in DFTs as an issue to investigate [22]. Our findings further our understanding of the underlying reasons for this distrust.

Participants in our study were frustrated that they had to put up with machines that fail so often. They wanted better tools that do not require them to babysit as they have better uses for their

time. They were also terrified of what DFTs could do, based on the catastrophic failures they experienced or witnessed. Imagine a professional tool that asks for its user to sit and watch while it operates, because it might catch on fire.

Thus, there is a real need for DFTs that fulfill the promise of safe and reliable operation without constant monitoring. To meet this need, we need to develop DFTs with better sensing capability in three areas:

- Awareness of performance – DFTs need to sense and validate the results of their actions in the real world. A professional tool would know if it is pouring filament over a ‘bird nest’ print or if its bit just crashed into its bed. Results-guided rather than process-guided tools that have the potential to be both more error-resistant and easier to program. For example, a performance-aware laser cutter programmed to *cut through material*, rather than to *cut at 50% power* is more resilient to material variation. It can course-correct its settings based on results, and go back to partially re-cut the parts it did not cut through in the first pass.
- Awareness of workspace – DFTs need to be aware of their workspace to avoid collisions, damage, and injury. This awareness should extend to static objects like the workpiece, fixturing clamps, or clutter forgotten on the machine bed, as well as dynamic obstacles such as users leaning into the tool’s working zone. In many cases, this awareness is both productive (e.g., providing improved material registration and tool-path validation) and essential for safety (e.g., detecting an over-heating workpiece before a fire breaks out; emergency-stopping rather than cutting through an operator’s hand).
- Awareness of self – DFTs should have knowledge of the current status and configuration of their parts. They should know what end-effectors are installed, and if those end-effectors are in working order. For example, they need to be able to tell if the nozzle is clogged or if the bit is broken. They should sense and react to changes in the status of parts that are critical for their operation, adjusting settings when laser optics are dirty, or pausing when coolant runs out.

In addition to providing an immediate positive impact on the felt work experience and performance of professionals; these DFT awarenesses provide essential building blocks for further positive expansion of fabrication tool intelligence.

Intelligent DFTs as Assistants

We probed professional users about where they would value machine support. They wanted an intelligent tool to work like a shop assistant rather than a collaborator: it sets up the machine, registers material, notes details in the material that will require a deviation from the norm, it knows how this machine is working, it calibrates, and it monitors the work as the work is being done. It makes suggestions when asked, but in a way that can be overridden.

This metaphor of a reliable and trustworthy shop assistant reveals a huge opportunity for machine intelligence, sensing, and actuation to support professionals in fabrication work, without challenging their autonomy. Future DFTs could automate low

Design Implications	Effort	Desire	Design Implications	Effort	Desire
Awareness over Performance			Awareness over Self		
Detecting failure*	Medium	Many	Sensing changes in the status of parts*	Easy	Many
Assessing and accounting for accuracy/precision*	Medium	Few	Self-adjusting settings to compensate for wear	Medium	Few
Course-correction based on detected results	Hard	Many	Re-planning in response to wear	Hard	Few
Detecting the quality of its operations*	Hard	Some	Personal and Collective Awareness		
Negotiating time/quality/cost trade-offs	Hard	Some	Documenting personal use*	Easy	Many
Allowing users to express high-level outcomes	Hard	Some	Utilizing logs for maintenance and error diagnosis	Medium	Some
Awareness over Workspace			Discovering and suggesting various new settings	Medium	Some
Detecting over-heating and fire prevention*	Easy	Many	Realization of actuation capabilities (e.g. finishing)*	Hard	Some
Performing material registration*	Easy	Many	Detecting use patterns for personalized settings	Hard	Some
Detecting obstacles in workspace*	Medium	Some	Collective awareness through data collected from multiple users and tools	Hard	Few
Optimizing work plan based on supplied material	Hard	Few			
Ensuring alignment across devices	Hard	Few			

Table 2. Design implications prioritized by potential difficulty (Easy: sensors exist, minor system integration is required; Medium: prototype exists, more integration required, some research may be needed; Hard: new technology needs to be developed) and value (number of participants interested in the idea: Few; Some; Many). Asterisk [*] indicates that similar features exist on some high-end DFTs.

level tedious tasks to free up users' time and attention, and leverage their machine capabilities to augment the process beyond human abilities. To achieve this, DFTs would need even more awareness over themselves and their environment.

This idea of DFT-as-assistant builds on the awarenesses discussed in the previous section. A better DFT could recognize the type of material, perform self-registration and orientation, and optimize work area based on design and material properties. DFTs could ensure alignment across devices (e.g. between laser cutters and CNC routers) for a smooth workflow. In addition, it could detect the quality of its operations, and self-adapt based on this feedback. For example, an enhanced laser cutter could sense its engraving quality based on the tint of engraving, start light to self-adjust its settings in real time, and allow its user to partially assign light and dark areas. In addition, it could adapt based on feedback from the shop manager – telling a laser cutter “your engraving is too light” might trigger it to revise its performance-awareness metrics to better align with its manager's goals.

Additionally, DFTs could leverage their machine capabilities to extend human capacity and augment the current fabrication workflow. An advanced DFT could take advantage of its ability to log and recall and present the already existing usage data in a way users can benefit from. It could keep track of settings, materials, time spent, and the results produced, and then cross-reference these to reveal patterns of use. It could learn from this data to provide personalized analytics, suggestions, and documentation to help users grow their skills. Moreover, future DFTs could utilize these logs for maintenance and error diagnosis, and self-adaptation. They could provide feedforward on when to maintain parts or self-adjust its settings to compensate for the wear on their parts.

Just as skilled fabricators might discuss their techniques on shop forums, DFTs could take this personal awareness to a higher level and gain collective awareness through data collected from multiple users. This would allow future tools to improve and refine their operations collectively by flag-

ging events that lead to failures. It would also enable DFTs to discover new patterns, including various settings used for different materials. However, it might prove challenging to collect both positive and negative samples along with all the other parameters, such as materials, hardware and software configuration. Developing infrastructures to enable the collection and making sense of this data in a privacy-preserving manner offers a clear space for future research. We imagine existing platforms that provide some of this data (e.g. Thingiverse [44]) could be leveraged in support of this.

This study also surfaced the lack of support in post-processes in current DFTs. Extending the capabilities of DFTs through sensing and actuation to remove some of the tedious work in post-processes is another fertile area for future improvement. DFTs should take advantage of their machine precision and perform additional work on objects that are already registered and have a computed tool path. Could a CNC router pick up a sanding disk and do a first pass sanding? Moreover, DFTs could help detecting the accuracy and precision of the workpiece. Could DFTs utilize optics technologies to assess and account for tolerances? We encourage HCI researchers to explore the integration of quality inspection, assessment, and treatment in DFTs to provide assistance in post-processes.

DFTs that Negotiate Trade-offs

Our findings highlight decision support in making trade-offs as a space where future intelligent systems can bring value. Our participants found it difficult to make trade-offs between time, quality, and cost during the fabrication process. While DFTs offer the capability to adjust many parameters that implicitly control these trade-offs, they do not do a good job of supporting professional's decision processes by connecting the controls to the outcomes, connecting outcomes to more abstract notions like quality, or by doing any optimization in support of a particular, preferred high-level outcome.

Fabrication systems most often assume that users know the quality they want. However, our study indicates that this assumption is not always true. Many participants in our study

shared that trade-off decisions are influential in their design process. Therefore, trade-offs are not single optimal solutions, they are emergent in the situation. Our participants struggled to express their intent even when they knew the quality level they desired. This seems to stem from the abstract interfaces of DFTs that does not help users in making sense of the settings.

A better DFT would work to both understand what measurable output factors (surface roughness, grain direction, discoloration of material, dimensional accuracy, material efficiency, etc.) are desired by the user, and to communicate how choices about these factors would influence its ability to operate effectively. It could help users to arrive at a set of trade-offs by, e.g., leveraging decision-support techniques or intelligent sampling approaches; rather than forcing users to struggle through a trial-and-error process. DFTs should recognize that desired qualities often vary within the same object, and should provide the ability for users to specify different quality levels for different parts within the same object/material. Further, tools should support decision making by revealing and negotiating these relationships early in the design process.

Negotiating these trade-offs again requires DFTs to have an awareness of their own capabilities and the quality they are producing. They would need to introspect the dimensional accuracy and the surface smoothness of the outcome, such as a wooden furniture that has a smooth surface finish and precision for tight fitting joints. How does a machine gain knowledge about its own quality versus its speed? What is a high quality cut/print, and how does it relate to the speed of an operation? Answers to these questions have the potential to transform the felt experience of making time, quality, and cost trade-offs in DFTs.

Developing DFTs that could gain awareness over quality individually, and build a database collectively might prove challenging, yet merit further study as a step towards intelligent DFTs. Our participants developed such awareness over months and years of practice to be more fluent in making trade-off decisions. DFTs with the ability to communicate and negotiate their capabilities could potentially expedite this process, enabling users to grasp hidden possibilities and build intuition.

Reflections on Autonomy and Agency

A core goal of our study was to explore the boundaries between machine autonomy and human agency in the context of professional users. Our study revealed rich details illustrating the aspects that are critical to user agency in making, which introduces new opportunities for DFTs to incorporate.

Like others in the HCI community [50], we promote the idea of human-centered DFTs that increase people's productivity through the application of machine intelligence and autonomy while maintaining users' agency and a focus on what actions are meaningful. Our study demonstrated that professional users desire more automation in mundane tasks due to the unbalanced division of labor required by current DFTs. HCI researchers could advance DFTs by leveraging new sensing, actuation, and reasoning capabilities along with existing computational power. Central to this approach is to empower professionals in their work by making them feel they are becoming better at their job.

Our study surfaced some insights into professional users' perception of machine autonomy. First, users find it frustrating when they have to monitor an autonomous DFT; they feel this is disrespectful of their time as professionals. Future designs should avoid this dehumanizing behavior of requiring people to sit and watch the machine work. Second, professionals in fabrication tend to feel limited when they are not able to customize DFT settings and operations. DFT designers should be wary of paternalistic automation that restricts customization and experimentation. Achieving a spectrum of automation for error prevention and convenience while also protecting human agency marks a clear space for HCI research. Finally, our findings demonstrate that users are skeptical of "smart features" as those most often fail in automating tasks. Researchers and designers should be mindful of false positives in automation.

We encourage HCI researchers and DFT designers to develop DFTs with increased self-awareness as it has great potential to improve fabrication processes through automation, personalization, and negotiation. We suspect the described interaction patterns would generalize across DFTs, and would benefit professional users as well as other groups in digital fabrication. Finally, our fieldwork surfaced the lack of diversity among professional makers. Although this was an issue we had anticipated [1], we were surprised by the gender inequality. Future work should address this critical issue of underrepresentation.

Limitations of the Study

Our study had two limitations. First, we focused on professional users as they are an important stakeholder in the fabrication process, yet they present an underinvestigated group in HCI research. We note that there are several other stakeholders in the world of DFTs including machine operators and service providers. Further studying these other stakeholders is likely to reveal additional directions for innovation in DFTs, and may also reveal a significantly different view on automation replacing workers. Second, we had only 2 women out of the 23 participants in our study. While this was representative of the population, the diversity is an issue that some researchers have recently addressed [1], and certainly merits further study.

CONCLUSION

In this paper, we have presented an exploratory study to understand professional users' current needs and future desires in digital fabrication practice. We expanded previous work by advancing the understanding of the felt work experience of fabrication professionals in micro- and small-scale manufacturing settings. Our findings offer design implications for future tool development with the goal of enhancing the user experience in making. We strongly encourage HCI researchers and others to work toward better future DFTs by building tools with more awareness that can operate as super-human shop assistants; that can leverage machine intelligence to support decision making around trade-offs in fabrication; and that can, overall, make professionals better at their jobs without threatening their autonomy.

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