Exploring and Understanding the Role of Workshop Environments in Personal Fabrication Processes

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Growing interest in personal fabrication has resulted in many ways to ideate, design, and prototype, in addition to studies of who a maker is and the challenges they face. Less attention, however, has focused on the role of the environment in fabrication processes. By understanding how interactions with tools, fixtures, materials, and spaces shape workflows, we can better determine how to design the next generation of workshops, design tools, and fabrication equipment to support personal fabrication activities. To build this understanding, site visits and interviews at local makerspaces, fabrication studios, and workshops were conducted. These visits uncovered the rich practices and roadblocks generated by workshops today. The observations identified the importance of spatial layouts, territoriality and occupant agency, distributed knowledge, and organizational flux, among others, to design and fabrication processes. These observations were further synthesized into one possible direction for such spaces: *hybrid workshops* (i.e., environments that can leverage computation and responsive architecture to enhance a maker's ability to design and fabricate). This work identifies how such spaces could harness the rich practices and eliminate the challenges found with workshops today and discusses the technical innovations and philosophical questions that hybrid workshops will pose to the future of personal fabrication.

CCS Concepts: • Human computer interaction (HCI) → Field studies; • Interaction design → Interface design prototyping

KEYWORDS

Personal fabrication, making, DIY, makerspace, workshop, hybrid workshop, responsive environments, adaptive tools, distributed information, distributed knowledge, organizational flux, territoriality, environment agency

1 INTRODUCTION

With the widespread availability and adoption of digital fabrication technologies, activities that were once the focus of afterschool clubs or shop classes have become integrated within educational curricula and societal culture. Unlike decades prior, where one required years of training to design and prototype an artifact using artisanal hand tools, the pervasiveness of additive and subtractive personal fabrication technologies such as 3D printers, laser cutters, and desktop CNC routers, has expanded the breadth and diversity of individuals who partake in personal fabrication activities [67]. What once required professional expertise is now in the hands of pre-school children and the elderly [16, 54, 71, 73]. Contemporary research on personal fabrication has analyzed the "making" and "DIY" movement, and focused on understanding who takes part in making activities (i.e., Expert Amateurs [55], Makers [4], Hackers [63], and Everyday Designers [116]), their motivations for doing so [65, 74, 109], the workflows and processes they use [15, 19, 65, 66, 100], and the barriers they face [44, 99][1]. Arising from this growing body of research has not only been a foundational understanding of who designs, makes, remixes, and creates [8, 43, 81] and the sociopolitical and socioeconomic tenants of maker culture [31, 36, 102], but also the need for, and development and implementation of, a variety of techniques and processes to support the breadth of skills sets, workflows, and needs of makers [2, 25, 77].

With the democratization of personal fabrication technologies has come a diversity in the locations where such activities occur. Today, many design, prototype, and fabricate within formal and informal learning spaces such as in libraries, science

[1] Note that throughout this work, the term "maker" is used to refer to all the participants in personal fabrication activities for readability.

centers, museums, campus fabrication labs, or community spaces [13, 85, 101, 103, 117, 119]. Such public "fabrication labs" or "makerspaces" can occur in permanent, dedicated spaces (e.g., a common area within a school), or in temporary, "pop-up" locations (e.g., in the hallways of a museum or science center). Their openness naturally encourages collaboration, knowledge sharing, and creates a sense of community amongst occupants [13, 16]. Although these shared, public environments are where fabrication occurs today, many have already begun to ideate on the personal fabrication spaces of tomorrow. For example, research by Roumen et al. proposed "personal fabrication on the go" via mobile 3D printers and cell phones [93], McKay and Peppler proposed mobile MakerCarts [73], Kim et al. proposed Within-the-Wild fabrication [49], and Krishnan proposed Mobile Makerspaces for hospitals [54]. Beliefs that personal fabrication activities should only occur within dedicated, specialized environments are continually being challenged.

If personal fabrication activities are to continue in both traditional (e.g., workshops and makerspaces) and non-traditional contexts (e.g., on the go and in temporary spaces), it is imperative that an understanding of how the fixtures, contents, and design of such environments, in addition to how occupants interact and control them, will influence personal fabrication. Research has shown that interactions with the built world influence our cognitive processes and understanding [79, 80, 120]. As such, instead of thinking of makerspaces and workshops as simply places to house assemblages of tools, materials, and equipment, it is equally important to consider how the fixtures, surfaces, tools, and machines not only enable (digital) designs to come to life, but also help an artifacts' design, iteration, and construction. In some instances, aspects of the environment may only influence the finish or size of an artifact (e.g., the CNC router bed is only so large or only one type of lacquer is available), while in others, they could completely change the form or shape of a design (e.g., if one has access to a dynamic pin-based table [62] versus having to build their own series of jigs for drying). With the increased sensorization and intelligent use of actuation that has already infiltrated office environments and architecture [9, 11, 37, 53, 104, 108], the design of personal fabrication spaces for the latter 21st century will not only need to support the interactions between people and materials, but will also need to be valuable to the participants that are integrated within design and fabrication processes.

Although current work on personal fabrication has offered a better understanding of who is fabricating, where and why they fabricate, and what they are fabricating, there is little understanding of the influence that workspaces have on what is designed and fabricated. If the tools, equipment, and materials a maker has on hand, the sounds and sensations around a maker, and so on, play a vital role in how they design, prototype, and fabricate, an understanding of how the environments of today influence workflows and processes is needed. Although it has long been known that aspects of the environment such as lighting, noise levels, and office layouts influence our productivity [39, 60], there is little understanding of how these and other facets of an environment influence personal fabrication and the physical creation of artifacts.

Much like the observations of office workflows and desk organization in the early 2000s were used to reveal the challenges that knowledge workers faced [48, 69] and later informed the design of desktop software and cross-device interactions [83, 115], this work reports on in-situ observational sessions that were conducted at eleven local makerspaces, community workshops, and studios to understand the role that the personal fabrication spaces of today have on the design and fabrication of artifacts. The findings from these observational sessions not only revealed how such spaces were laid out and organized, but also how such spaces are dynamic, living entities that do define and scope the problems that are undertaken and dictate the manners in which occupants' experiment with, and create, artifacts. Among other results, the sessions illustrated that the practices commonly found in workshops today, along with the challenges that the design of personal fabrication workshops pose, including the ad-hoc, and often troublesome barriers imposed by spatial layouts, the need for adaptable, responsive surfaces and fixtures, agency and territoriality issues that arise when one wishes to control aspects of the environment that they cannot, and the necessity for contextual assistance to impart personalized knowledge. Also arising from these sessions was the need for a new type of personal fabrication environment, i.e., the hybrid workshop, spaces and environments that leverage computation and responsive architecture to enhance, when necessary, a maker's ability to design and fabricate artifacts. An analysis of the practices hybrid workshops could harness and challenges they could help overcome, the technical innovations that are needed, the philosophical questions that they raise, and two design fictions that explore possible instantiations of hybrid workshops, all underscore the work that needs to be performed before personal fabrication spaces can be of service to makers, instead of makers being limited by them.

This work offers three contributions to the literature on personal fabrication: (i) an analysis of the layout and organizational schemes used in eleven North American personal fabrication spaces today, (ii) an understanding of the practices and challenges personal fabrication spaces have on design and fabrication activities, and (iii) the proposal and exploration of the hybrid workshop. For those conducting research on smart environments, intelligent tools and materials, and personal fabrication, the data from the observational studies should encourage a reconsideration of the role that the spaces which makers design, ideate, and fabricate within have on the activities they undertake. The exploration of the hybrid workshop should similarly encourage discourse and reflection not only on how a workshop may be laid out, but also the very notion of what a workshop, studio, makerspace, or personal fabrication environment could or should be and the degree of assistance and automation that may be beneficial to integrate into future spaces.

2 RELATED WORK

Several foci of past work, including (i) the design and layout of makerspaces and workshops, and (ii) the workflows and methods by which we interact with the built environment, informed the present exploration into the role the environment and its contents have on personal fabrication activities.

2.1 Designing Makerspaces

Unlike the abundance of research that has focused on maker culture, less attention has focused on understanding the facets and implications of the *spaces* where personal fabrication occurs.

Work by Landwehr, Sydow and Jonsson [58], revealed that making occurs in two distributed arenas, (i) virtual spaces such as forums, tutorials, supplier websites, and social media platforms, and (ii) visible, physical environments where physical prototyping, material manipulation, and finishing occurs. Although there have been many studies examining the tenants of virtual arenas of making (e.g., [55, 92, 113]), this work focuses on the equally important role that physical environments have on design and fabrication processes.

In terms of the physical environments where personal fabrication occurs, a few guides and sets of best practices have been proposed to help with the setup of a physical makerspace. The Maker's Manual [110] and the Makerspace Playbook [68], for example, offer guidance on how to start-up and maintain makerspaces or communal workshops. They identify the roles patrons could embody, recommend tools and equipment to acquire, and detail pedagogical approaches and safety concerns to attend to. Work by Mikhak et al. reported on the experience and challenges encountered while setting up FABLABs around the world [75], whereas Darrin and Krill proposed that makerspaces need to be set up such that they are open 24/7, support mechanical, electrical, digital prototyping (along with design thinking), and are centrally and prominently located [24]. Many others have reported on best practices for integrating making within libraries, schools, and community spaces, such as the need for: dedicated staff, a curricula of interdisciplinary projects that be used to welcome newcomers, "buy-in" from multiple stakeholders, maintenance and replenishment schedules, strategies to acquire external funding and partnerships, workbenches and tables to promote collaboration, clear budgets and financial resources, necessary equipment, policies and documentation on safety, strategies to provide accessibility, and training materials and posters on common practices [1, 13, 16, 47 , 85, 87, 94, 101, 103, 117, 119]. Such resources are helpful, as they emphasize the importance of factors that many do not give attention to (e.g., budgetary constraints, external partnerships, and maintenance), they however also lack guidance on how to organize such spaces or the challenges that decisions about tools, surface, fixtures, and the environment itself will present to occupants, or the practices such decisions naturally encourage.

A few projects have specifically called out the layout or importance of environmental design on personal fabrication processes. Fleming recommended dividing spaces into "fixed" and "flexible" stations such that occupants could walk in and engage with certain equipment (i.e., fixed stations) or areas that could be replaced or removed and relocated to other spaces as needed (i.e., flexible stations) [28]. In their exploration of creative spaces on campuses, Thoring et al. delineate between five different types of spaces where learning and exploration can occur (e.g., spaces for deep work, collaboration, presentation, making, and intermission) and identified five different ways such spaces can enrich learning (e.g., organizational culture, knowledge, stimulation, social interaction, and infrastructure) [111]. Georgiev, Milara, and Ferreira applied Thoring et al.'s classifications to a FABLAB and determined that FABLABs are spaces exclusively for making, with different areas for 'tools & machines' and 'design spaces'. Kemp also provided a series of recommendations on the importance of layout in makerspaces, delineating between "loud work areas", i.e., areas for larger projects that require power tools, and "quiet work areas", i.e., areas for projects with little mess or noise [47]. No further details about the design or location of these spaces, or their implications, aside from noise and cleanliness were provided by Kemp.

Work by Posch et al. described the division of a FABLAB into a centrally-located design area where digital models were created, a perimeter-based fabrication area where occupants could produce physical artifacts, and a gallery area to show off finished creations [86]. Few details, however, were provided about the rationale for this layout. Darrin and Krill also recommended such a layout (including the addition of ample areas for storage), as they claimed it was ideal for collaboration and safety, as all occupants can see each other [24]. They, however, did not explore the implications of this categorization or the centrally- and perimeter-based areas in detail. Recent work by Lingel examined the personal workspaces of (semi-) professional craftspeople and identified the embodied nature of space organization, the importance of tool and equipment provenance, how workspaces encouraged flow, and the territoriality benefits that personal spaces provide [64]. The present exploration is similar to Lingel's in that this work focuses on how a space can serve its occupants, however it differs in that the present focus is on shared, multi-user, semi-public environments. In addition, the spaces that were visited in this work were used for hobbyist or educational purposes rather than professional activities.

2.2 Interacting with the Built Environment

From exploring the information that can be gleaned from office workers' usage of paper and supplies on their desks, to the ways in which our proxemic relations to entities can be used to influence them, to methods that have been proposed to control dynamic environments, exploring occupant workflows and environmental control has long been a focus within HCI.

Early work in the 2000s explored the relationships between office workers and the paper documents and office supplies that they use. Work by Kirsh [50] and Malone [69] for example, identified that office workers organized paper-based documents in piles and groups on their desks in ways that decreased the breadth of choices they would have to search through, thereby increasing their success of searching and retrieving a document at a later time. Work by Sellen and Harper demonstrated that office workers often organized their environments using piling, placing, shifting, and archiving techniques so as to visually demonstrate the progress that they had made throughout the day and increase information finding [98]. Such findings were echoed by Bondarenko and Janssen [14], Hong et al. [42], Mizrachi [76], and Takano et al. [106, 107]. Sellen and Harper also observed the proxemic role of documents to workers, classifying documents as "cold", "warm", and "hot" based on their distance from the worker [98]. Those documents that were "colder", i.e., farther away, were less important and infrequently consulted or used. Cole additionally found that "cold" documents were often spatially distant and organized in a haphazard manner [21]. Although the present exploration is focused on understanding how occupants work and move within workshops instead of office environments, the notion that spatial organizations can dictate the importance of entities, was also echoed in our observations of personal fabrication workshops.

More recent work has expanded the findings of Sellen and Harper to ideate how users can interact with entities that are closer or farther away from them. Great attention has been given to exploring how the distances, i.e., proxemic relationships, between the users and interactive entities within a space can be harnessed for interaction and control. As proposed by Vogel and Balakrishnan, the degree and types of control one can exert over an interactive entity can be specified by the distance the individual is from the entity and largely fall into four interaction zones: ambient, implicit, subtle, and private [114]. Echoing Sellen and Harper's "cold", "warm", and "hot" documents, the closer one's body is to an entity, the more functionality and personal information should be revealed. Common uses of such proxemic information have enabled the distance of one's body to modulate zooming [38, 51], the level of detail rendered in visual content [26, 27, 45, 46, 51, 70, 118], and the methods used to render or abstract information [46, 61]. Others have made use of additional proxemic properties such as orientation, movement, inter-user distances, and user identity to disable or control the functionality that is available [6, 33, 89, 97]. A slightly different usage of proxemic information has been to use a device to mediate interaction. Proxemic-aware controls, for example, enable an occupant to point and orient a tablet towards or away from other devices to invoke different levels and fidelities of control [59]. Although the present exploration does not specifically explore how proxemics could be used within a workshop environment, proxemics-based research inspired some of the themes that the research team set out to observe during the workshop visits.

Although the environments that we live and work in have yet to become fully automated or intelligent, many have explored the ways environments, surfaces, and fixtures could adapt to occupant and users. Kona and Uddin put forth that architecture and environments should behave similarly to the movement of organisms, i.e., linearly, angularly, radially, in spirals, by contracting, by expanding, by deforming, by folding, by retracing, by shape-shifting, or by metamorphosis [53]. Unfortunately, although they hypothesize that entities will self-erect and autonomously change, they did not elaborate on how an occupant could invoke such movements. Takeuchi distinguishes between three different types of intelligent habitable environments: responsive architecture (i.e., shape- or appearance-changing architectural structures and entities that use actuation or visual methods to transform), augmented environments (i.e., built environments remain unchanged but utilize illusory visual alterations created via augmented reality techniques), and printable environments (i.e., built environments that don't change but are replaced using additive manufacturing) [108]. Like the present exploration, Takeuchi argues that habitable environments will need to dynamically adapt with little notice and require minimal interaction from the user, however little detail is provided on the methods of interaction aside from the use of voice commands.

Others have explored the techniques and methods that could be used to exert control throughout a space or over an entity. Coelho and Zigelbaum proposed that interaction with shape-shifting interfaces (of which dynamic fixtures and surfaces could be considered) should be explicit, most often through touch-based interaction [20]. Rasmussen et al.'s survey of shape-changing interfaces categorized possible interactions as those where (i) no occupant action induces a change, (ii) an occupant is unaware that their actions are inducing a change (e.g., implicit input), and (iii) the occupant is explicitly touching, pointing, squeezing, or so on, the object or entity they wish to control [90]. In-air gestures or gestures made in the surface of the display are also popular techniques for use with shape-changing surfaces, as evidenced by their use in Recompose [12], Relief [61], inFORM [30], and Materiable [78], among others. Lakatos' AMPHORM surface also made use of gestural interaction, but additionally proposed the usage of contextual information to augment the gestures being performed [56]. On a larger scale, the ExoBuilding proposed using physiological data from an occupant for interaction with kinetic architecture [95], whereas with the InteractiveWall and InteractiveCurtain [11], the mere presence of an occupant would automatically create openings or deformations in a wall. Most interestingly, the MuscleTower explored the use of autonomous reconfigurability by using the tower's own movements to invoke changes in its façade [82]. Although this is but some of the research conducted on responsive architectures and interactive surfaces, there has yet to be a holistic understanding of the appropriate methods for interacting with such entities, or the implications that the varying degrees of control that they afford have on feelings of agency. The present work used the breadth of modalities that such research explored to inspire the fictional realizations of hybrid workshops in Section 4.

3 STUDY OF EXISTING MAKERSPACES AND WORKSHOPS

As fabrication occurs within a variety of locations, this work sought to develop a holistic understanding of how the spaces, surfaces, fixtures, tools, materials, and equipment within a personal fabrication environment support design and fabrication processes. The research team investigated the increasingly popular *semi-public* spaces where diverse groups of patrons (e.g., casual makers, artists, engineers, students, and so on) can fabricate, either by a patron joining a local space or by a patron gaining access via their school or community. As such spaces have diverse patronage, they must also accommodate the most general of skill sets and widest range of activities. They are thus an important collection of spaces to explore as they share similar goals yet achieve them in markedly diverse ways. They present a unique opportunity to understand the tenents underlying the role of an environment on personal fabrication workflows and processes today.

3.1 Workshop Recruitment

Initially, a list of twenty-one local spaces in and around the metropolitan area of Toronto, Ontario, Canada, which self-identified online as hackerspaces, makerspaces, art studios, or workshops, was compiled (i.e., spaces or environments where makers designed, constructed, built, and refined products or projects either individually or collaboratively). Fifteen spaces that were open to the public or part of post-secondary institutions were contacted and ten gave permission for visitation and study (Figure 1, Table 1). As an interviewee in one of the workshops recommended an eleventh that had recently opened, permission was granted to visit this space as well. Note that the spaces were located in a variety of areas throughout the metropolitan region of Toronto and were not concentrated within one neighborhood or socio-economic area. The choice of sites is thus both a strength and limitation of the presented work. It is a limitation in that not all results and findings may apply to makerspaces in different parts of the world, however, as the metropolitan area of Toronto is one of the most multicultural in Canada, the spaces and occupants represent a diversity of making environments and cultures that could be

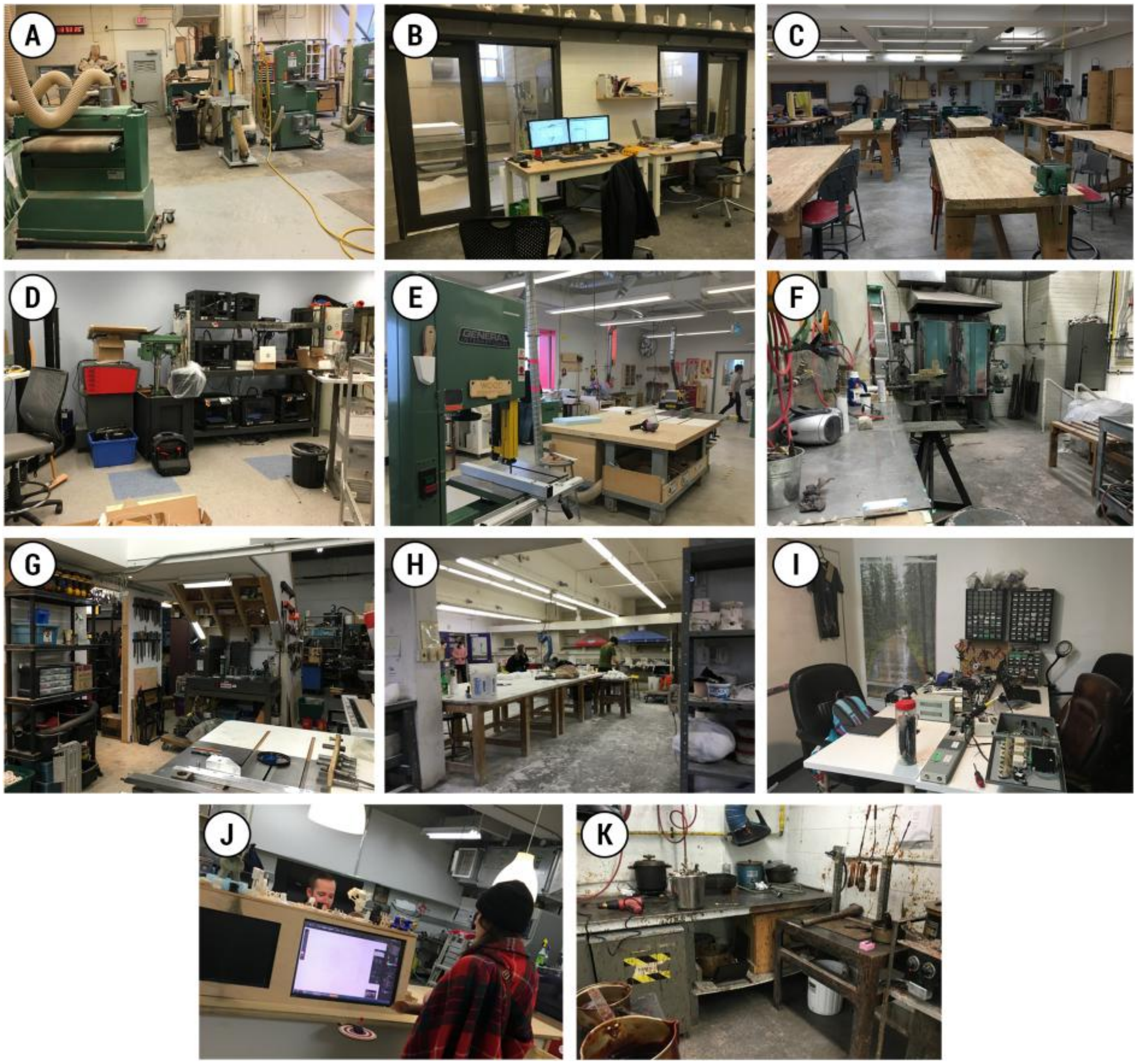


Figure 1. Examples of the workshops that were recruited: (A) Architecture Model Studio, (B) Digital Fabrication Studio, (C) First-Year Teaching Shop, (D) Grad Space, (E) Industrial Design Studio, (F) Metal Foundry, (G) Metal Shop, (H) Mold Making Studio, (I) Multi-User Makerspace, (J) Rapid Prototyping Center, and (K) Wax Studio.

found in other makerspaces and workshops throughout North America today. As a variety of workshops, studios, makerspaces, labs, and centers were visited, all spaces are referred to as *workshops* for readability.

3.2 Data Collection and Analysis

The lead researcher observed each workshop for between one to three hours, observing approximately 85 people across all eleven workshops. In some cases, the workshops were visited when the space had general open hours where anyone could access the space, while in others, the spaces were observed when a class was in session or a specific group was working in the space. The observational periods focused on attending to process workflows, tool usage, layout and organization, digital technology usage, collaboration, and sensorization. To ensure the confidentiality of some projects and to decrease potential distractions and safety issues that could arise from the presence of video cameras and charging cables, observational notes were taken on pen and paper or a pen-enabled tablet. The lead researcher also took photographs of each workshop and drew annotated floorplans of each workshop, noting the locations of work surfaces, equipment, materials, tools, and so on. These floorplans were later digitized and redrawn using Microsoft Visio.

Table 1. Details about the eleven workshops visited during the observational sessions.

WORKSHOP	TYPES OF PATRONS	PATRONS PER HOUR	APPROXIMATE AREA	ACTIVITIES SUPPORTED
Architecture Model Studio	lab assistants, shop stewards, students	5 - 15	190 m^2	Design, creation, and finishing using wood, metal, plastic, foam, rubber
Digital Fabrication Studio	instructors, shop assistants, students	1 - 5	40 m^2	Design and prototyping using 3D printing, laser cutting, and waterjet cutting
First-Year Teaching Shop	students, instructors	10 - 50	260 m^2	Design, creation, and finishing using paper, wood, metal, plastic, Styrofoam
Grad Space	general public, university students, professors	1 - 5	110 m^2	Design and prototyping using 3D printing, simple electronics and circuit boards, sewing
Industrial Design Studio	industrial designers, shop stewards, students	10 - 30	320 m^2	Design, creation, and finishing using foam, plastic, plywood, sheet materials, wood; painting and finishing booths
Metal Foundry	artists, shop assistants, students	1 - 5	30 m^2	Creation of molds, lost wax casting, pouring of molten metals, finishing of metal sculptures
Metal Shop	engineers, hobbyists, wood workers, students	1 - 5	160 m^2	Design, creation, and finishing of version one prototypes using wood or metal
Mold Making Studio	artists, sculptors, students, shop stewards	5 - 15	230 m^2	Armature building, life casting and piece moulds, plaster, concrete, plastic, and rubber moulding,
Multi-Use Makerspace	general public, high school and college students	10 - 40	360 m^2	Design and prototyping using 3D printing and laser cutting, simple electronics, dark room photography, DIY biology, amateur radio
Rapid Prototyping Center	general public, operators, students, instructors	5 - 20	60 m^2	Design and prototyping using 3D printing, laser cutting, CNC routing, 3D scanning
Wax Studio	artists, shop stewards, students	1 - 10	170 m^2	Design, creation, and finishing of wax and clay sculptures or moulds

In all workshops, the founder/manager and 1-5 other makers(s) were also interviewed, with the number varying based on the foot traffic in the workshop (total = 36; 14 female). Interviewees were chosen based on their willingness to take part, not their gender, perceived age, or the project they were working on. Of those interviewed, fourteen interviewees' full-time jobs were to manage and help makers, two were engineers or professors/instructors, one was a woodworker, twelve were post-secondary students, and three were artists. Note that each interviewee occupied the workshop for several reasons, most of which were not location-specific (e.g., in educational workshops, students not only worked on course projects, but also on portfolio or hobby projects, STEM outreach activities, start-up prototypes, or freelance activities).

For each interview, a semi-structured interview format was used, where makers were asked about their project and goals, what they (dis)liked about the workshop, and tool and technology choice. Each interview lasted a minimum of 10-25 minutes (the maximum was 65 minutes). Managers were also asked about patronage, layout, technology usage and acquisition, safety, sensorization and desired equipment, and so on, topics which a review of [35, 44, 59, 64, 66, 68, 110, 112, 114] highlighted as being potentially important. In locations where noise levels were too loud or where students were present, notes were taken via pen and paper or on a pen-enabled tablet (due to the post-secondary institutions' policies). In all other locations, interviews were audio recorded.

After data collection, the field notes and informal interviews were digitized (i.e., the audio and handwritten files were transcribed to Word documents), then printed out and cut up into individual paragraphs or fragments. This data, along with the photographs taken of each workshop and the hand-drawn schematics, were used by the lead researcher for an affinity diagramming activity that manually grouped and regrouped the data according to the observations and themes that emerged. The strips of paper were used in lieu of the post-it notes most commonly used for affinity diagramming due to the length of some comments and observations. This affinity diagramming process allowed for an identification of organizational, workflow, and behavioral patterns common across all workshops that were visited. Systematic coding techniques informed by the organizational patterns were used to further synthesize the data [105].

3.3 Workshops Visited

This exploration into personal fabrication workshops is focused on the nuances of the environments where design and fabrication activities take place today. As such, it is important to have an understanding and context of (i) the type and number of occupants of each space, (ii) the activities that each space supports, (iii) the equipment present in each space, and (iv) the organizational layout of each space. Such information grounds the observations, identified practices and challenges, and environmental design implications that are reported. Thus, the work first introduces each of the eleven spaces that were visited and presents schematic layouts of each space (Figure 2 and 3). An analysis of the schematic layouts and the findings from the observations follows in Section 3.4.

3.3.1 Architecture Model Studio

The Architecture Model Studio was part of a local post-secondary institution. Its purpose was to provide students with the equipment, tools, and materials necessary to transform CAD or hand-drawn models into large or small-scale prototypes. Most commonly, students worked with a variety of foams and woods using traditional woodworking machines and tools such as drill presses, table saws, band saws, and so on. The space also had a variety of hand tools and sanding machines, so students could manipulate plastic, metal, and rubbers. The space was a single room divided into different areas and was overseen by shop stewards who maintained the space and assisted students when necessary (Figure 2a). The space was primarily used for open lab hours to complete course and graduate projects.

3.3.2 Digital Fabrication Studio

The Digital Fabrication Studio was a smaller scale space that housed 3D printers, a laser cutter, and a waterjet cutter. It was designed to fulfill the digital fabrication needs of undergraduate students at a local post-secondary school enrolled in architecture and environmental design classes who create low and hi-fidelity prototypes using 3D printable plastics, woods, and foams. The space did not have any hand tools or areas for refining the artifacts that were created – students had to go to a different area of the school to perform such tasks, if desired. The space was unsupervised and composed of three rooms (one for design and low-fi prototypes made from printable plastic and two others for higher-fidelity prototypes made from wood and foam; Figure 2b). The space was open to students as part of open lab hours.

3.3.3 First-Year Teaching Shop

The First-Year Teaching Shop was a large, two room space that was used to teach basic woodworking and prototyping skills to a variety of first year art and design students at a local art and design school (Figure 2c). The students primarily worked with a variety of woods either using woodworking machines such as a table saw, bandsaws, routers, and sanders, or traditional hand tools such as chisels, hand planes, and so on. One room was used for instruction, design, and working with simple hand tools, while the other housed the powered woodworking tools. Many shop stewards and instructors kept regular office hours and aided students when necessary. A section of the instruction room had some powered woodworking tools that were used by instructors to demonstrate how they worked. They were off limits to students. The space held both open lab hours for any employee of the school, in addition to scheduled classes for first year students.

3.3.4 Grad Space

The Grad Space was a medium-sized makerspace that was part of a larger research lab at a local university (Figure 2d). It was used by both graduate and undergraduate students in Library and Information Sciences to create interactive prototypes and artwork. It housed many 3D printers, a sewing machine, a desktop PCB machine, and a variety of hobbyist electronics. Students primarily worked with wood, metal, plastic, Styrofoam, and paper. The space was maintained by the graduate students, who decided what equipment to buy and materials to acquire. It was open to the general faculty of the department, and also made available to the public for a few days each month.

3.3.5 Industrial Design Studio

The Industrial Design Studio was a two-room workspace that supported the design and assembly of industrial and environmental design prototypes in one room and prototyping and finishing tasks in another room (Figure 2e). It was used by senior undergraduate students at a local art and design school during class hours as well as during open lab hours. The space was monitored and stocked by shop stewards. In this space, students primarily worked with a variety of woods, but were encouraged to experiment with different finishes and finishing processes. The fabrication room housed traditional woodworking equipment such as sanders, grinders, drill presses, lathes, table saws, and so on, as well as plastic-specific equipment such as a spray booth and a vacuforming machine.

3.3.6 Metal Foundry

The Metal Foundry was located at the same art school as the Wax and Mold Making Studios (detailed later), and was located in a separate space near the Wax Studio, however, it was observed and is analyzed separately due to the differences between the spaces (i.e., the processes of making a mold are unique to those of using the mold in a foundry; Figure 2f). Once a student or artist had a mold, they could bring it to the one-room Foundry to create a bronze or aluminum form or sculpture or patinate a previously created metal form. Due to the inherent dangers in using molten metals, the Foundry was open during a restricted set of times and monitored by a shop steward. Only senior students and approved artists could use the space.

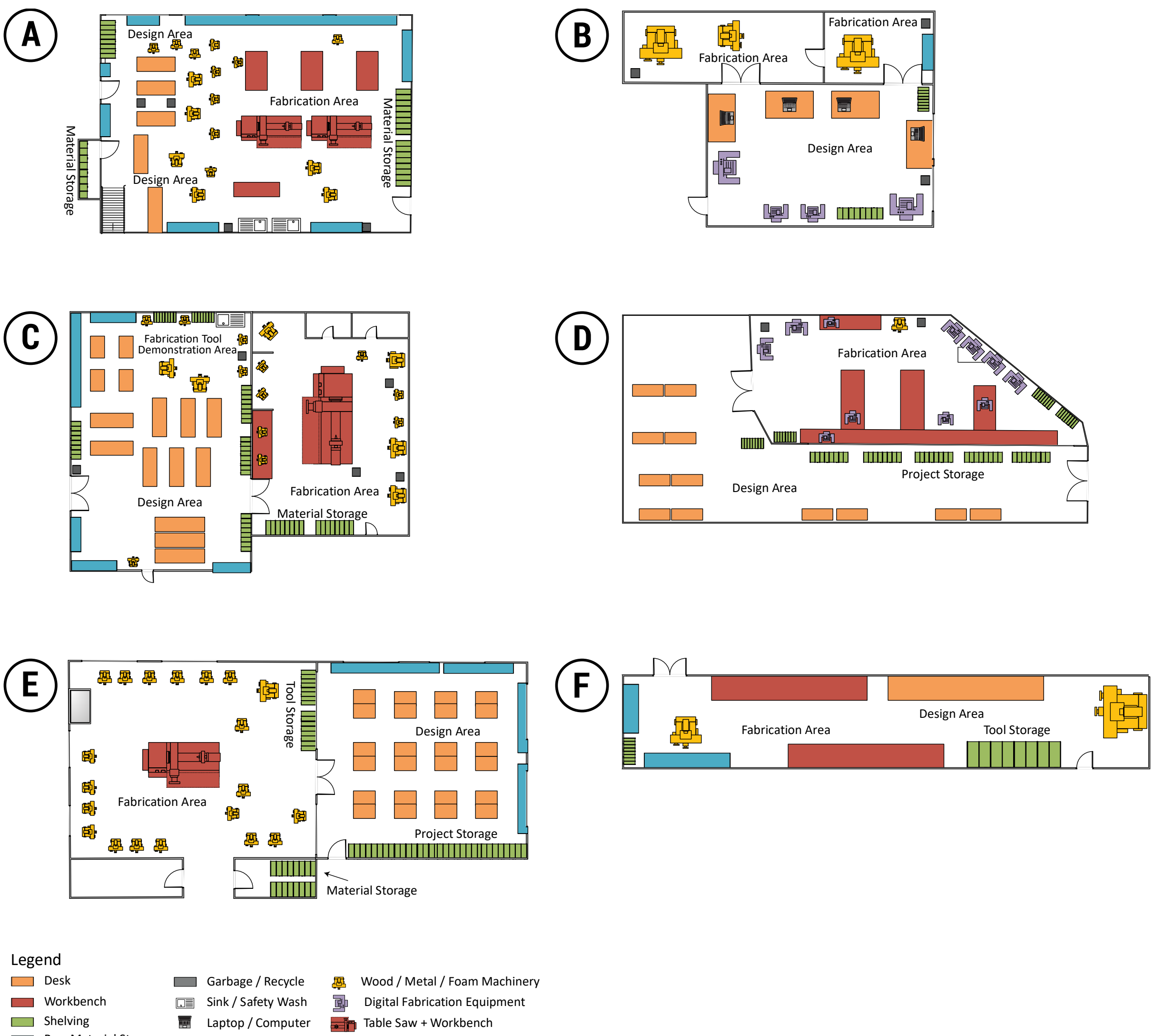


Figure 2. Floor Plans of the (A) Architecture Model Studio, (B) Digital Fabrication Studio, (C) First-Year Teaching Shop, (D) Grad Space, (E) Industrial Design Studio, and (F) Metal Foundry. Note that the floor plans are not to scale.

3.3.7 Metal Shop

The Metal Shop was a community-based fabrication space that allowed students from a variety of high schools and post-secondary institutions, in addition to members of the general community such as engineers, woodworkers, and hobbyists, to build metal and wood "version one prototypes". The space was housed in a two-level garage (Figure 3a) and contained a variety of hand and powered machinery, including a CNC mill, table saw, drill press, metal bender, and so on. The makers in the space paid for monthly access and the space was run by a retired toy designer who provided assistance or would build "version one prototypes" for his own clients.

3.3.8 Mold Making Studio

The Mold Making Studio was part of the same institution as the Wax Studio, however it supported students and artists in the creation of waste, piece, and flexible rubber moulds for the creation of art, prototypes, or life casts. In this single room space, makers had access to a variety of plasters, cement, silicones, clay, latex, rubber, and alginates (Figure 3b). Side rooms were used solely to hold additional materials. Equipment was at a minimum in this space due to the nature of the molds that were supported, however simple hand tools and scales were available. A shop supervisor was available to answer questions and order material, but left makers to their own devices. The one-room space was open to all members of the art school, in addition to local community artists.

3.3.9 Multi-User Makerspace

The Multi-User Makerspace was a community-run makerspace that was housed in a multi-room space (Figure 3c). All equipment and tools were donated by the community or purchased via fundraising. The purpose of the space was to encourage artists, programmers, designers, and hardware hackers to learn new skills, share their skills and knowledge, and contribute to larger projects. The makers in the space worked on a variety of projects, such as school projects, startup prototypes, and community-initiatives. Each room in the space housed the equipment and tools necessary for different fabrication tasks, including a DIY biology lab, an electronics lab, a wood/metal shop, and a photography dark room. The space also had a variety of tools, such as hobbyist electronics, microscopes, thermocyclers, a desktop centrifuge, a laser cutter, 3D printers, hand tools, a router, and a drill press. Each member paid monthly dues to join and maintain the space.

3.3.10 Rapid Prototyping Center

The Rapid Prototyping Center was a single room area within a local post-secondary school that would print or create 3D prototypes for students and faculty (Figure 3d). It was run by a dedicated staff that was versed in digital fabrication techniques and equipment and used 3D printers, 3D scanners, laser cutters, and a CNC mill. Patrons would bring their designs to the Center and the staff would consult with them about their design and then fabricate and finish it for them. It was common for one staff member to serve students and another to run the equipment and clean up prints or finished artifacts. Patrons paid for their finished prototypes and did not have access to the machines themselves.

3.3.11 Wax Studio

The Wax Studio was a single room space that supported design students and artists in creating wax and clay sculptures (a sub-space was available for hazardous material molds made from silica, however, we were not granted access to this space and it was restricted to a sub-group of trained students; Figure 3e). The studio had a variety of equipment to create sculptures from wax, lost-wax castings, or molds that could be later used to create clay, wax, or metal sculptures. Equipment consisted of powered woodworking tools, including polishers, drill presses, bandsaws, sanders, and sand blasters, as well as hand tools for the finishing of the molds. The Studio had a dedicated supervisor and staff that would help with the maintenance and usage of the equipment during open lab hours. The space was open to all students and faculty at a local art school, in addition to local artists.

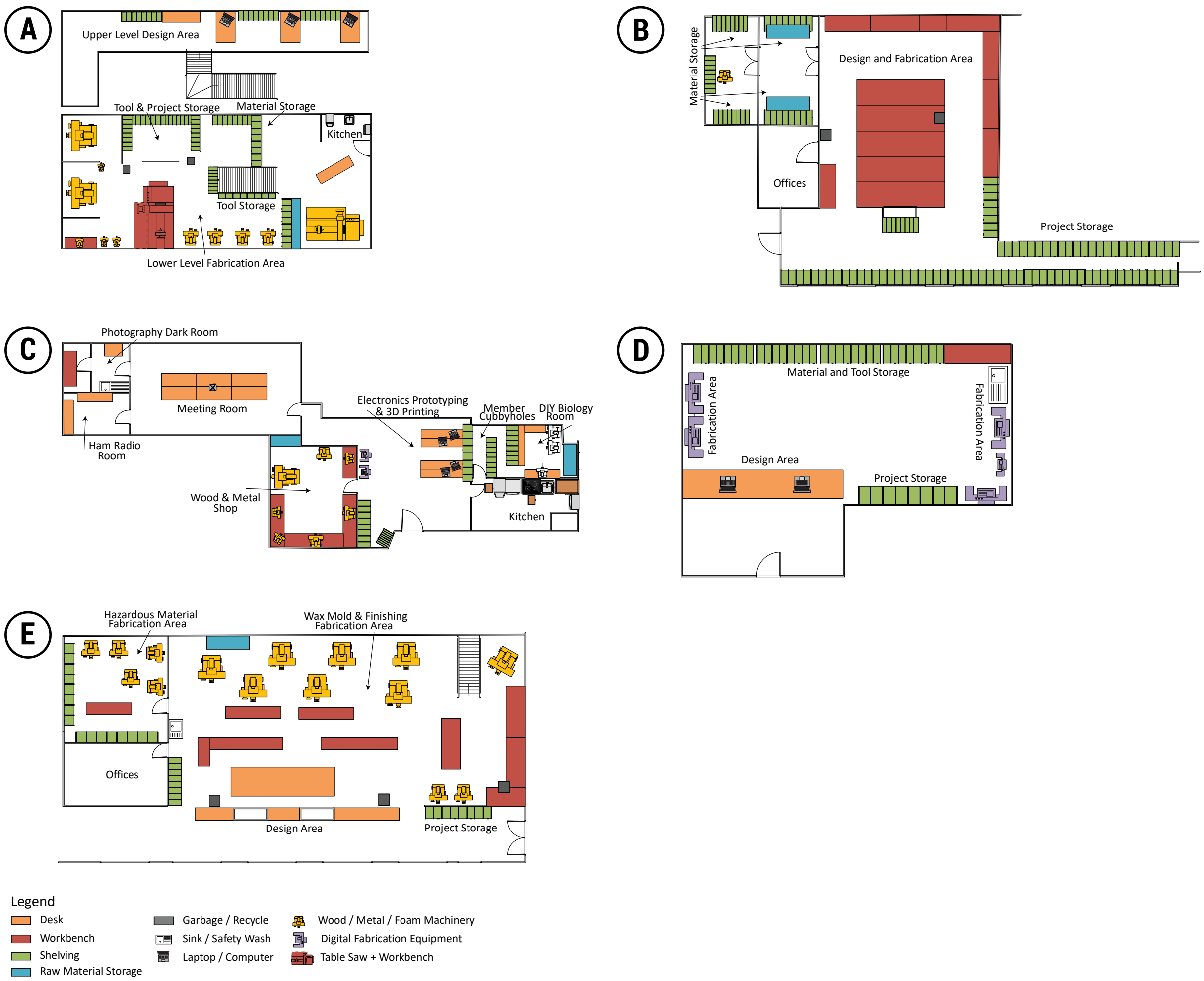


Figure 3. Floor Plans of the (A) Metal Shop, (B) Mold Making Studio, (C) Multi-Use Makerspace, (D) Rapid Prototyping Center, and (E) Wax Studio. Note that the floor plans are not to scale.

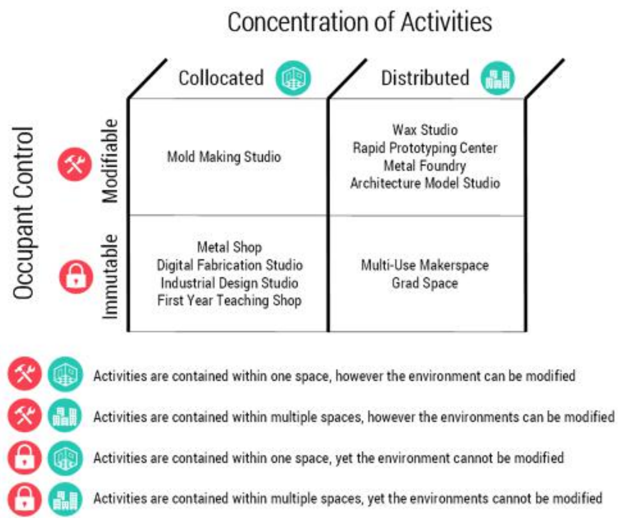
3.4 Rich Practices and Challenges Found Within Workshops Today

The outcomes of the affinity diagramming and systematic coding technique processes, in addition to the photographs, interviewee comments, and layout schematics uncovered not only the rich role the environment and its spatial organization play in personal fabrication workflows and processes, but also a number of challenges that the contents of an environment (i.e., materials, tools, other makers, and so on) can impose on personal fabrication activities.

3.4.1 Barriers Imposed by Spatial Layouts (O1)

Although each workshop served a different population of patrons and activities, every workshop had areas for design, ideation, fabrication, and finishing. The spatial layouts of the workshops differed, however, in the location where these activities occurred (i.e., collocated versus distributed) and the degree of control an occupant could exert over the contents of the environment (i.e., immutable versus modifiable). Four layouts were thus observed: collocated modifiable, collocated immutable, distributed modifiable, and distributed immutable (Table 2).

Table 2. The classification of the four types of environmental layouts (i.e., Concentration of Activities) and the flexibility of each space (i.e., Occupant Control) that were observed.



3.4.1.1 Collocated Activities with Modifiable Occupant Control

In the first category of spatial organization, all the activities within a space occurred in one area that could be reconfigured as needed. Within the Mold Making Studio, where makers worked with plaster, concrete, plastic, and resins, workbenches with marble tops were found around the parameter of the entire space, in addition to the center of the room (Figure 3b). There were no desks or heavy machinery in this space, so workbenches and projects could move around as needed (according to the workshop manager, this did not occur very often, but was possible). This flexible layout enabled makers to work with whatever material, in whichever location, whenever they wanted.

Aside from occasionally walking to the side storage rooms to get more material or some hand tools, the layout enabled makers to largely stay in the same space and not walk around. One maker really enjoyed how he could concentrate and "*get lost in my own world because I get here and grab everything I need and I don't move until I want to go home*" (Mold Making Studio). For this maker, the ability to remain at a fixed location was highly beneficial and enabled him to work and concentrate in a manner that "*none of the other places I've been let me just be … everything's in arm's reach"*.

Further in service of the flexibility of the space, the managers had also made several storage trolleys, that makers could load up with tools or materials and park next to the workbenches, available for use. This was in part due to the weight of some raw materials, but also so that it was easy for makers to pick up and move to another area if needed. One student was observed quickly packing their tools and artifacts on a trolley and moving to the other side of the room as soon as another student started to vigorously shake concrete on a table behind them. This maker was visibly annoyed that they had to move. In this situation, the openness of the space encouraged makers to perform whatever task they needed to at their own pace but didn't provide a (physical) barrier to prevent distraction or decrease the potential annoyances or irritations of others.

As these two observations demonstrate, although the environment was designed to support collaboration through openness, it unintentionally discouraged participants from interacting with each other because they become so engrossed in their work that they didn't notice what was going on around them. For those who were watching or paying attention to others, the freedom and trolleys within the space enabled makers to move around with ease. In the case of single room designs, it thus appears necessary that workshops need to have methods to maximize task flow, while also offering opportunities and solutions to create temporary boundaries that can be called upon or dismissed on-demand to overcome the irritations and annoyances that such open environments enable.

3.4.1.2 Collocated Activities with Immutable Occupant Control

In the second category of workshops, the layout was such that there were dedicated, immutable zones within the environment specifically designed for certain activities. The Architecture Model Studio, Metal Foundry, Rapid Prototyping Center, and Wax Studio, all followed this format where a single room was divided into visually distinctive areas or zones (Figure 2a, Figure 2f, Figure 3d, and Figure 3e, respectively). For example, desks used for design or meeting activities were found near each other in rows or a grid layout along one side of a room or wall and were often bolted to the floor or were so heavy that they could not be easily moved. Quite often, no other fixtures, materials, or tools were nearby, aside from stools (this was also the only location with seating in the workshop). The workbenches that were used for construction or finishing were often found near, or next to, hand tools, equipment, and machinery. Similarly, these workbenches were difficult to move around due to their steel construction. Although makers could have worked with their laptop on a construction or finishing bench, this behavior was not observed.

Because design and fabrication activities were distributed across two locations, it was quite common for makers to work on a design or measurements on a laptop or sketchpad in one area of the room, and then move to a dedicated fabrication zone, either around the parameter of the room or on the opposite side of the room, to begin prototyping. When they needed to consult an online resource or their digital design, they often took their prototype with them to their desk, found the necessary information, then went back to their workbench and continued constructing or finishing. There was thus quite a bit of movement and transitioning from one side or zone to another. Although the proximity between the zones was usually less than 10 or 20 meters, the division between the "design" and "fabrication" area was not found to be too irritating for participants, with many of them welcoming the distinct visual zones, i.e., *"I can see who is working on stuff and who isn't ….. if I needed help, I know that the people over there [gesturing to workbenches along the side of a wall] could be doing things where me interrupting could be a safety hazard so I won't even look to see who is there, I'll look at the others who are sketching or on their computers over here*" (Wax Studio).

In terms of fabrication itself, because many of the tools or equipment were in fixed locations, makers often walked between multiple locations to complete tasks. For example, one maker in the Architecture Model Studio first started at the table saw, then walked to the drill press, went to the sander, walked back to the drill press, walked back to the table saw, etc., all while carrying not only their prototype, which was quite large and heavy, but also any hand or finishing tools they needed (e.g., sandpaper, pencils, small pieces of their prototype, measuring tapes, and so on). Although the various equipment that this maker used was within an approximate 5-meter radius, this maker became visibly frustrated whenever they left a hand tool at the last machine they were using, if someone else had jumped on a machine and changed the settings from what they had set it to, or when they had to make multiple trips to carry all the tools and supplies they needed to a new machine. In this case, the maker found it very difficult to complete their task because "I *basically regroup every time I move to new equipment which just sucks because I waste so much time moving from machine to machine … if I forgot the [measuring] tape at the sander, I would really stop and think how important it was for me to go back and get it or if I could just guess the size I needed … I end up wasting so much material because I mess up*" (Architecture Model Studio).

When the shop founders or managers were asked why the workshop was organized into distinct zones and areas, many commented on equipment requirements (e.g., the Rapid Prototyping Center needed to have the laser cutter near the only area in the room where the exhaust could be located), safety reasons (e.g., the Metal Foundry furnace was in a low traffic area), or to encourage cleanliness due to the materials used in the workshop (e.g., Wax Studio).

Based on these observations, the division of design and fabrication into different areas can drastically change how makers perform fabrication activities and the experiences they have while doing so. As the observations from the Architecture Model Studio demonstrated, when fabrication tasks must be distributed throughout a space, there is a subsequent opportunity for technology to not only detect and retrieve all the tools and equipment that are necessary to improve efficiency, but also to provide makers with visualizations and reminders of the task at hand to ensure task continuity. Of course, an alternative to this could be to autonomously relocate machinery itself, however, this would come with ducting, power, and ventilation concerns. These observations also demonstrated that one benefit of having such zones is that they quickly provide a wealth of information about the activities that are occurring, although intelligent maker tracking and notifications via augmented reality headsets could provide similar information.

3.4.1.3. Distributed Activities with Immutable Occupant Control

The third organizational layout that was observed was also the most frequently used. Within the Digital Fabrication Studio, First-Year Teaching Shop, Industrial Design Studio, and Metal Shop, the workshops were divided into two (or more) distinct rooms (Figure 2b, Figure 2c, Figure 2e, and Figure 3a, respectively). One room housed desks and small workbenches that were used for design and ideation activities. These often took the form of individual or two-person desks that were made of wood and were bolted to the floor or wall (or were so heavy they prevented movement). The other room(s) had the hand tools and equipment that were available to makers. Hand tools were often located in named and friction-fit cabinets or shelves, whereas larger equipment was typically in areas in the space near safety posters and exhaust vents. In some workshops, such as the First-Year Teaching Shop and the Industrial Design Studio, all the tools and equipment were located throughout the room, around the parameter or on workbenches scattered throughout the space. In other workshops, such as the Metal Shop and Digital Fabrication Studio, dedicated rooms held a specific piece of equipment (e.g., one room for a CNC machine, and a separate room for a lathe). In these spaces, every piece of equipment, desk, tool, and material had a specific location. Makers could not rearrange fixtures as they needed or take tools from one area into another.

Some managers indicated that the workbenches and desks were not movable and in different areas due to safety issues or lab rules around cleanliness "*so that the kids don't turn this place into a messy zoo that I'll have to clean up*" (Industrial Design Studio). In the case of cleanliness, makers appreciated the rules and zones because they prevented their neighbor, who might be a stranger, from "*sanding wood next to my new laptop because that sawdust would get everywhere, and they wouldn't care but I sure would*" (First-Year Teaching Shop). These workshops often had high throughput and equipment and machines that could pose a danger to makers if they were distracted while using them.

In these workshops, makers performed design and fabrication activities in distributed areas. Much like the Collocated Activities with Immutable Occupant Control workshops, makers sat on a stool at a workbench or desk. After creating their design on their laptop or on paper in the "design" room, makers walked (or took the stairs) to a "fabrication" room. As "fabrication" rooms did not accommodate idea iteration (i.e., no desks or stools), one had to walk back to a "design" room if they needed to consult an external resource like a YouTube video or product sheet, or if they needed to make a change to their digital model or design. Unlike the Single Room layouts, fluid transitions between design and prototyping were not supported. Makers spent much time walking between the spaces (which could have been on different floors as in the Metal Shop), often leading them to became distracted and break their flow and concentration. On the other hand, some makers preferred to stay in the fabrication area and "*wing it – I just guess and hopefully it will work out ... but yea, this is my pile of failures [gesturing to a disjoint pile of wood]" (*First-Year Teaching Shop*)*. For these makers, the spatially disjoint design and fabrication activities left them surrounded by many failed ideas and materials (e.g., holes or cavities with the wrong dimensions, or parts attached incorrectly).

One benefit of these disjoint spaces was that makers spent quite a bit of time creating their initial design before walking over to a fabrication space. This was because there was more collaboration between makers than in the single rooms, perhaps because they recognized that everyone in that space was performing a creative task and could benefit from a break or conversation every now and then. As one maker in the Digital Fabrication Studio said "*I wouldn't dare talk to someone who's in the other rooms because 1. I wouldn't want someone else bothering me and 2. It could be so unsafe … but over here with the computers and 3D printers it's not so serious".*

When asked why the two (or more) areas were divided, one shop manager (Industrial Design Studio) remarked that they needed to "*limit the distractions that all newbies succumb to when being in the presence of equipment*". They appreciated that the two rooms made it difficult for newcomers because they could not explore, iterate, and refine in the same area, however the safety benefits and concerns and cognitive boundaries the rooms imposed outweighed the workflow limitations (i.e., makers would have to pay attention when asking for help on the design side rather than make repeated mistakes over and over because they just wanted to start using the machines when on the fabrication side). The manager of the Metal Shop indicated that they had more dangerous equipment in separate rooms for safety and noise reasons (e.g., "*you have to go out of your way to get in there*") and that the upstairs design area allowed makers to focus and not be distracted by others who were using trial and error approaches in the main fabrication area downstairs. For both of these managers, the distinct areas not only ensured safety and minimized disruption, but also followed how they both viewed personal fabrication – composed of two distinct activities, "*well you first need a plan [design] and then once you have that plan you see what will actually work* *[fabrication] … it's so rare for the final product to look like the plan that really the plan just lets you organize your ideas*" (Metal Shop).

In line with the observations from Collocated Activities with Immutable Occupant Control, this layout further underscored the opportunities and challenges that physical walls pose on the design and troubleshooting decisions made by participants. When information was not available on-demand, makers had to weigh the importance and cost of going to find it. This speaks to an obvious need for techniques to call up, search, read, and comprehend relevant tutorials and help videos in situ, rather than to have to go to another room to seek them out. Further, it also suggests that the current methods used to create sketches and illustrative drawings do not necessarily align with the increasingly iterative and precise nature of personal fabrication – makers need to use input devices and output mediums that are robust to the environmental demands of a workshop so they can make changes on the fly and see renderings or calculations immediately, either in CAD-type software or as visual augmentations overlain on their artifact.

3.4.1.4. Distributed Activities with Modifiable Occupant Control

The last category of workshops made use of multiple rooms but had flexible layouts and organization in these rooms. We only saw two examples of this, in the Multi-Use Makerspace (Figure 3c) and in the Grad Space (Figure 2d). The Multi-Use Makerspace could support a variety of design and fabrication activities; however, each room was specialized for a certain type of design and fabrication activity (e.g., a darkroom, a ham radio room, a DIY biology room, an electronic prototyping room, etc.). Within every room of this workshop, makers ideated and designed right next to the equipment they were using and had the freedom to move the equipment and tools around as they desired, except for sinks due to the plumbing required. In the Grad Space, only two rooms were available, but makers could reorganize them as they needed. Makers would often work entirely in the "fabrication area", rather than at the desks in the "design area".

As the tools for ideation and prototyping were co-located in both spaces, makers switched between both activities in an interleaved manner, similar to the spaces observed in Collocated Activities with Modifiable Occupant Control. Within a given space, it was common to see makers have their laptop or sketchpad open next to the hand tools or machinery they were using and making edits to a sketch or model as they worked. As one maker noted, "*being able to reference and modify this sketch and look at things on YouTube really makes it easier and faster for me to work because when something isn't right I can easily look up how to fix it or change my design to reflect the mistake I made*" (Multi-Use Makerspace). Unlike the Collocated Activities with Immutable Occupant Control layouts, however, it was also common to see makers working together and sharing tools. These behaviors may be due in part to the smaller sizes of the spaces themselves (rather than occupying one large giant room, or two rooms of about equal size, smaller spaces about a quarter or fifth of the size were available). The openness and collaboration opportunities that the smaller spaces afforded may have been further influenced by all makers in a given sub-space working with similar materials and equipment. In each space, the alignment between makers' goals and tasks created a sense of community that encouraged them to work together and take risks. This layout *"allow[s] our makers to really get their hands dirty and make mistakes and discoveries simultaneously"* (manager, Multi-Use Makerspace).

Two downsides emerged with such a sub-space organization. First, in the Multi-Use Makerspace, the entire workshop became a collection of smaller sub-spaces, which discouraged participants from learning and sharing with others in other spaces due to the physical barriers that existed between the sub-spaces. While there were two common spaces in the Multi-Use Makerspace (i.e., kitchen and a meeting room), many makers worked in the space that aligned with their current project and would rarely "travel" to other spaces. Unlike the other multi-room workshops and the Grad Space, the lack of a common thread across the entire space prevented a cross-pollination of ideas. Second, although all tools and materials within the spaces were largely within reach and proximity, due to the smaller size of the spaces, whenever there were too many makers or projects took up too much physical area, some makers had to collect a number of tools and pieces of equipment and move into another space (i.e., the meeting room in the Multi-User Makerspace, Figure 3a; the Design area in the Grad Space, Figure 2d). They thus created a less well-equipped, second temporary space so they could work. This came with its own set of challenges because makers then had to move between both spaces to find tools and equipment, work on desks or benches that were not suited to the activities they were performing (e.g., too short or wide), relocated from the temporary to original space when they were finished, and limited activities to those that would not create a mess, loud noises, or lingering odors.

These observations demonstrate the influence of larger, more multi-faceted spaces on design and fabrication activities. If activities are contained within the same space and all require equipment, fixtures, and elements that are part of that space, there is no need for additional technological innovations (with the exception of solutions to overcome noise, odor, or environmental requirements imposed by strangers in the space). On the other hand, they also suggest the need for intelligent techniques to determine which activities can be collocated or relocated based on the number of makers in the space, the health and safety requirements of the activities, and knowledge about the physical areas that are available. Responsive architecture and adaptive surfaces may be able to offer some solutions to overcome the need for temporary areas that can meet the demands of makers and their projects, although they will also require techniques to invoke and dismiss such architecture that will work within the cleanliness requirements and noise restrictions of such spaces.

3.4.2 Organizational Flux (O2)

As mentioned, all spaces were visually similar to a stereotypical workshop and had an organizational schema to house material and organize smaller hand tools. Some workshops housed tools next to associated machinery, e.g., the Industrial Design Studio had chisels in form-fitting slots under the lathes (Figure 4). This allowed tools that were needed before, during, or after using a machine to be within arm's reach, enabling quick access and preventing distractions and accidents. Within the Grad Space, the resting spots for materials and tools were less rigid, but still exhibited a spatial organization. Similar to Lingel's [64] and Sellen and Harper's [98] findings, tools used most recently were within reach, closest to makers, whereas those used in the past were pushed aside, into the periphery. The Metal Shop used an embodied approach to tool organization, with tools found in maker-specified resting places that had evolved over time. This process worked well because makers' behavior and workflows, rather than a lab manager or the constraints of the space itself, dictated the location of tools.

Figure 4. Chisels located in the base of a lathe enabled easy access to them.

Although such schemas facilitated tool localization, all makers, except those in the Mold Making Studio and Rapid Prototyping Center, wasted time finding tools, due to flux. What was in one location one minute could be in a different location a minute later. One maker wished he "*could dictate where everything was so I could bring all the tools I use close to me and hide everything I don't use*". In workshops where design and fabrication were not co-located, such as in the Industrial Design Studio, makers scavenged to find tools, as they were not returned to their form-fitting or labelled locations and were instead on others' desks or buried under scrap materials. In some ways, this limited the techniques that makers could use because they had to know the entire inventory of tools that were available and exert time and effort to find a given tool, make do with whatever tool they could see after a quick visual search, or change some elements of their design. In many cases, the tool they found may not have been the appropriate one they needed, e.g., "*I tried to find some grittier sandpaper but couldn't so I am working twice as hard sanding this piece of wood using this paper with less grit … it's really annoying*" (First-Year Teaching Shop). In the two locations where flux was not observed, occupants either exerted control over all of the tools that they needed (Mold Making Studio; see Section 3.3.3), or due to scheduling, only one person worked with equipment and tools at a time so they had control over the entirety of the space (Rapid Prototyping Center).

These organizational observations speak to a frequent, and irritating problem with workshops today: flux and movement naturally shift the location of tools, materials, and fixtures when multiple makers are present or when one needs to move around the space frequently. In spaces with a single occupant, flux may not be a problem, as the lone maker is the one relocating and customizing the environment for themselves. In public workshops or environments with multiple makers, there is a definite need for tool and equipment localization systems so that the environment itself can have an awareness of its tools and materials, in addition to interaction mechanisms and visualization techniques for makers to become aware of, and locate, equipment they need.

3.4.3 Territoriality to Exhibit Agency and Control (O3)

As all workshops were multi-occupant and makers were free to work at any workbench, environments were not personalized or permanent. Makers used a variety of temporary visual cues such as using backpacks, coats, or sticky notes to stake claim to areas (Figure 5a). Others used less explicit methods, such as repurposing visual remnants of past activities (e.g., "*hey, I am using all of this desk up to that gash on the right side*"; Industrial Design Studio). In workshops such as the Mold Making Studio and First-Year Teaching Shop, we saw makers exhibit hoarding behaviors, amassing the largest possible area, taking ownership of every tool and piece of equipment they could possibly need and configuring the equipment to project-specific setups (even though they were not needed immediately; Figure 5b). Unlike personal spaces, which have low competition for resources and can be highly customized [64], for these makers, these behaviors ensured that they could complete their task and not fight for space or equipment. Because these makers could not have any other forms of control over the environment, they established their territory and exerted their desire to control the space using tools, surface, fixtures, and materials. These results echo those found by Brown and Brown and Zhu with office workers [17, 18].

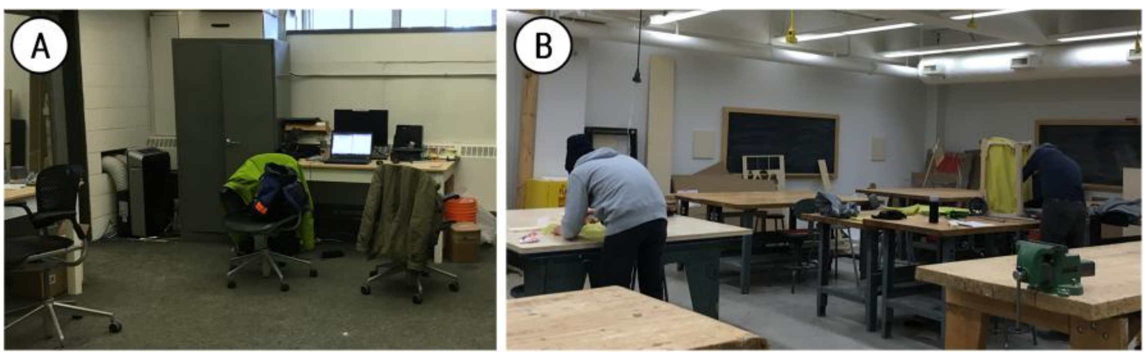


Figure 5. Territoriality behaviors were exhibited in a number of ways. (A) In some spaces, such as in Digital Fabrication Studio, non-permanent personal property such as backpacks or coats were used to stake claim to the space one was using. (B) In other spaces, occupants amassed a very large space, often larger than needed. The two students shown here, in the First-Year Teaching Shop, were working together on the same project, yet hoarded and spread out their tools and materials across three desks.

Being able to reconfigure the location of desks or tools in environments with flexibility prevented makers from having to work within the limitations and (physical) boundaries of a space. Instead, it enabled the fixtures and tools to be in service of the maker. This flexibility, while common in private environments such as homes or private offices, is non-existent in many workshops today due to the necessity for workshops to have high throughput and support as many different types of potential projects as possible. Further, when makers in the Multi-Use Makerspace, Mold Making Studio, and Grad Space were free to reconfigure and customize the environment to their liking, they were more open to exploring new ideas and taking risks because they felt comfortable and in control of the environment and what they could do "*being able to move things around and gather everything I need here on my desk and organize it the way I need is a huge advantage …. It's like I'm at home, except my home doesn't have all these tools and I don't need to clean up*" (Mold Making Studio). Given the mutable nature of personal fabrication workshops, fixtures, tools, and machinery today, it is not surprising that the impersonal and sterile feel that most environments had impacted maker's outcomes, "*it's the kids that come in here and own the space, those are the ones that do some really cool and interesting things … the shy ones who keep to themselves don't experience a lot of skill growth and we often don't see them again*" (manager, Mold Making Studio).

The different territoriality behaviors exemplify the impact that a maker's feelings of control and agency over a space can have on their, and others', experiences when fabricating. Although fabrication environments should be generic enough to accommodate a variety of makers and tasks, they need to balance interpersonal dynamics, resource allocation, and distractions. Spaces need to have an awareness and intelligence about of the range of customizations and personalization opportunities that they support and relay this functionality to makers in ways that will educate them on how, and to what degree, they can control their surroundings, along with the impact of their activities on other makers and projects.

3.4.4 Meeting the Needs of Many Through Limited Tools and Equipment (O4)

During the observational sessions, makers made everything from wooden tables to laundry carts, set pieces, art installations, model houses, chess sets, motorcycle parts, and so on. Such diverse projects needed many different tools, however, makers never seemed to have the right tool [8, 112]. This was not a byproduct of poorly equipped workshops, as the workshops had most of the basic tools recommended by the Maker's Manual [112] and Makerspace Playbook [68]. In most cases, not having the right tool was due to personal preferences or commercial tool manufacturing limitations. In the Mold Making Studio (which had seventeen types of chisels), one maker carving a plaster bowl said, "*I mainly use this smaller [chisel] because it is what we have, but I would much rather have something that would fall between these two [gestured to a bigger chisel] because it would be the perfect size and it would be faster*". In this case, the maker wanted a tool that manufacturers did not make. In the Industrial Design Studio, several specially constructed jigs were handmade by a shop steward to secure the raw materials that the Studio sold to students to a table saw (Figure 6a). These jigs filled workshop-specific needs that were imposed by the materials that the school could order and as such, the jigs could not be bought commercially.

Figure 6. Specialized accessories that were created to overcome limitations with workshop tools: (A) a series of milk creates acting as weights to help with the lamination of a series of wood strips in the First-Year Teaching Shop and (B) a taper jig for use with a table saw was used in the Industrial Design Studio because a commercial version could not be found.

Materials told similar stories. One student's design in the First-Year Teaching Shop needed a long slab of multi-colored wood. As the workshop did not have any laminates, the student had to use his own lamination process, jerry-rigging a collection of small clamps, wooden milk crates, and weights to make the material he wanted (Figure 6b). In other cases, such as in the Architecture Model Studio, makers themselves became fixtures. While working on a bench-sized curved form, three students appeared to be working collaboratively, however, further observation revealed that two of the students were simply 'muscle', holding various sections because there were not enough shims or supports to hold the large form being created.

In all cases, although the workshops had an array of tools that met most needs, even the most basic of tasks, e.g., shaping plaster or supporting a component, required highly specific or personalized tools made precisely for the task at hand. The ad hoc need to create and use specialized tools, materials, and supports can influence the future of making in many ways. Environments could encourage makers to create their own such solutions to problems, as this would educate, encourage, and expose makers to exercise critical thinking or utilize other fabrication techniques or tools. Depending on the intention and skill level of the occupants of a space (i.e., a personal workshop versus a learning environment for novice students), there may also be a need for fixtures, surfaces, and tools that can adapt to the needs to a maker, techniques to invoke or modify them as needed, and methods to dynamically adjust tools on-demand.

3.4.5 Distributed Inspiration (O5)

An unexpected theme that emerged was how some storage decisions unintentionally inspired makers. Most of the "design" spaces contained shelving and examples of work that was in the process of drying, was an abandoned endeavor, or was a work in progress (Figure 7). The contents of the shelving thus formed a pseudo-gallery and many makers were seen browsing the shelves for ideas. As one shop manager said, "*the shelves started as utility because the desks were so full of projects no one had anywhere to sit but now they are nice to walk by and see how [name] is doing or what [name] finally gave up on*" (Industrial Design Studio). In these spaces, makers looked at remnants left in the shop, pondered for a few minutes, then walked back to their workbench, and began sketching. The remnants thus served as inspiration and helped form new ideas. When design and fabrication were collocated, this was quite helpful, as makers could observe and be inspired by materials, software, tools, and mistakes simultaneously, unlike distributed environments where inspiration could only be gleaned from the remnants of design or fabrication on shelves.

Figure 7. Shelves in the Wax Studio and Mold Making Studio were used to store (A) discarded artifacts and (B) works in progress, however they also served as a source of external inspiration for makers.

The provenance and visual history of most workshops was also prominent, with remnants [3] relayed where machines and tools used to be or activities that occurred in the recent past (e.g., varnish spills, paint overspray on the wall, wood scraps near a lathe, and so on). Although these artifacts are the by-products of others' design ideas and processes, they were observed being used for inspiration and learning (e.g., *"oh yea, there used to be a spray booth over there … hey, maybe you could try using a spray-on coating instead of a brush*"). In the Metal Foundry, many past makers had trouble (and some success) with patina finishes. A shop steward kept the students' failures and created a chart to use as a teaching reference and inspiration board for others and mounted it on the wall near the entrance of the space (Figure 8).

Although makers' ability to find sources of inspiration within workshops was surprising, this finding invites one to consider how explicit interaction or visual storytelling with the augmentation of remnants in an environment could be harnessed to support further ideation and prototyping inspiration.

Figure 8. A chart of patina examples in the Metal Foundry that were created out of many student successes and failures.

3.4.6 Distributed Tacit and Explicit Knowledge (O6)

All workshops had some form of help or assistance available, whether it was via senior members providing tacit knowledge by demonstrations or signage illustrating explicit knowledge such as processes or safety. In the First-Year Teaching Shop and the Industrial Design Studio, an 'expert' shop steward would demonstrate some aspects of a tool and then allow others to try it themselves. While enabling makers to experience the most "hands on" and direct way to gain tacit knowledge, this process was time-consuming for shop stewards, as they had to continually fix the same errors and were prevented from helping those with irreversible mistakes or complex fabrication challenges. Some shop stewards expressed a desire for systems that could allow students to experience demonstrations first hand to reduce mistakes, "*it would be great to record myself performing a technique and have a robot or something watch each student and tell them what they are doing wrong or prevent them from hurting themselves - I can't see everything*" (Industrial Design Studio).

Although there were posters and other notices throughout each space to provide explicit knowledge, half of our interviewees felt that they spent too much time reacquainting themselves with tools they had not used in a while. Because such spaces were shared, makers did not have the luxury of leaving equipment setup as they needed or time to hone their skills with a particular tool (e.g., *"I know how to use a table saw, but I don't know the intricacies of this one",* Industrial Design Studio*).* Although some equipment had signage showing it should only be used for one type of material (e.g., 'Plastic'; Figure 9a), because there were no manuals or instructional tutorials or posters nearby, it was difficult for makers to remember which steps were necessary for each piece of equipment and which settings to use (Figure 9b). Most often, makers would have to interrupt someone else and ask them how to use equipment. This workflow, while informative, could be dangerous as it relies on correct information being passed from person to person.

Similar practices were observed when it came to materials, especially those that could not be immediately used. Much like makers must wait hours for a 3D print to finish before declaring success [44], there were frustrations related to waiting for materials to settle. One maker in the Mold Making Studio said, "*if we could simulate how our materials would turn out beforehand or be told where our concrete hadn't settled enough before hardening, it would save me so much time because I don't use it that often and I waste too much time when things fail*". In the case of this maker, working with materials such as wood was easy because it offered immediate feedback when manipulated, however epoxies, resins, concrete, and other such materials required one to consult product sheets and online information to understand its usage and immense patience to wait to determine if it had been used properly.

Figure 9. Examples of the "documentation" and assistance that could be found in the (A) Industrial Design Shop and (B) Wax Studio. The 'Plastic' sign informed participants that the bandsaw could only be used for plastic but did not provide any other instructions. The only instructions for the grinder were the 'red' and 'green/white' labels on the outer casing and the hand-written sign indicating the location of the light switch.

The desires of makers and managers to be able to access enhanced methods to gain information illustrates one of the biggest challenges within workshops today: all equipment, tools, and materials need an onboarding process and require a literacy that cannot be formed overnight. Given the diverse skill set of makers, the current need to re-learn techniques or material information suggests the need for hands-on, augmented tutorials and safety monitoring techniques that not only teach makers how to use tools and equipment but also demonstrate and visualize the potential outcomes that could result from their appropriate or inappropriate use. If coupled and augmented with the rich information that is often passed from person-to-person in workshops today, personalized, contextually-aware visualizations, tutorials, and feedback appear paramount to the next generation of workshops.

3.4.7 Limited (Intelligent) Environmental Technology (O7)

Not every space that was observed was setup for digital fabrication. Only in the Multi-Use Makerspace, Metal Shop, Grad Space, Digital Fabrication Studio, and Rapid Prototyping Center were digital fabrication technologies such as laser cutters, 3D printers, or CNC mills found. As mentioned, all other locations had more traditional equipment such as lathes, planers, routers, kilns, metal furnaces, and hand tools. All makers did however, have access to laptops, cell phones, and tablets; technology usage was not restricted in these spaces.

Seven workshops made use of building automation techniques to control lights, modulate power to machines, and turn ventilation and dust collection on and off. Following local safety standards, the First-Year Teaching Shop and the Industrial Design Studio installed sawdust sensors within their ducts to sense and prevent sawdust fires. Managers indicated that "*such automation helps limit the number of safety steps [they] need to remember to decrease the anxiety and learning curves that I see infrequent or novice makers experience*" (First-Year Teaching Shop). None of the workshops, however, had 'intelligent' sensing systems or 'smart' machinery. The owners of the Multi-Use Makerspace and Metal Shop wished for equipment that would perform its own maintenance or measure usage frequency, as many makers had difficulty troubleshooting, determining the current state of shared equipment, working in a safe manner, and cleaning up after themselves. Such technology would help decrease the time managers had to spend on such tasks and would enable them to work more closely with makers on their designs and helping them to improve their fabrication skills. Based on the desires of management, and not makers, there appears to be an opportunity for environmental automation via tracking and sensing systems, at least in the form of clean up, reconfiguration, safety and status monitoring, and maintenance.

3.5 Opportunities and Challenges for HCI

From dictating workflows via spatial barriers to encouraging alternative designs via unintended inspiration, the observational sessions illustrated that workshops perform a greater function than simply housing material, equipment, and tools: they often influence and dictate how makers design and prototype. They thus encourage a number of rich practices but can also lead to a number of challenges. It was surprising that something as simple as the choice to divide a workshop into different zones resulted in the distributed workflows that we observed, or that the natural movement of tools throughout a space would encourage the hoarding behaviors that occupants exhibited. The following seven environmentally-encouraged practices and imposed challenges were derived from the aforementioned observations and were found to most strongly influence personal fabrication processes today (Figure 10)[2].

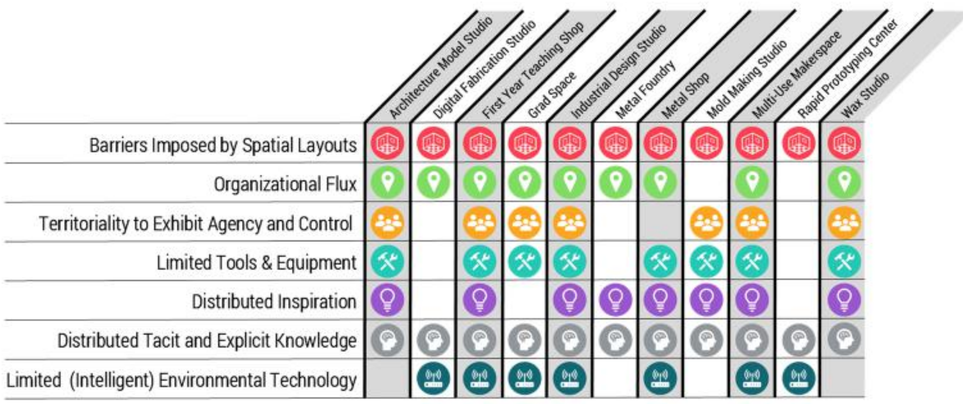


Figure 10. The seven observation themes that were uncovered in the eleven workshops that were observed.

1. Spatial Barriers (O1): The use of one versus multiple rooms and fixed versus flexible room layouts prevented or encouraged collaboration between makers. These spatial layouts also encouraged makers to perform design and fabrication activities in different ways, sometimes discouraging both activities from occurring in an interleaved manner. This lead to frustration, a loss of flow, and avoidable trial and error cycles and failures.
2. Organizational Flux (O2): The natural movement and relocation of tools and equipment throughout a space did allow makers to temporarily create a more personalized workspace, however flux also made it difficult for makers to see what tools were available and to find the correct one for the task at hand. This lead to lost time spent searching for tools and unnecessary frustration, especially when multiple makers were in an environment.
3. Territoriality for Control and Agency (O3): Given that spaces are designed to accommodate a variety of projects and makers, and are often not designed by the maker themselves, they are often too generic and lack the specificity and personalization makers desire. On one hand this resulted in hoarding behaviours, whereas on the other, when a maker felt in control of the space and tasks they were performing, they felt supported to take additional risks.
4. Limited Tools and Equipment (O4): Although most spaces were outfitted with a range of tools and equipment, many tasks required project-specific tools, support systems, or settings. When a necessary tool was not available, it was either custom made (if the maker had the ingenuity and time to develop a solution), a poor equivalent or substitute was used (which could result in errors), or the maker's design was modified to adapt to the tools at hand.
5. Distributed Inspiration (O5): Remnants, works-in-progress, and failed experiments were often used as sources of inspiration. When such sources of inspiration were co-located in spaces that supported both design and fabrication, they enabled makers to quickly iterate over their design, or sparked new ideas.
6. Distributed Tacit and Explicit Knowledge (O6): Knowledge about tool, material, and equipment usage was not contained within one maker or location in the space, but rather distributed across multiple makers and external resources. While rich with information, such resources were often difficult to access or make use of, especially if contained within another area or zone.

[2] Herein, each observation is abbreviated as O1 – O7. These abbreviations are used throughout the remainder of the article to refer to these seven observations whenever a finding or concept that appears later in the article relates to, or exemplifies, one of the observations.

7. Limited Environmental Technology (O7): Although most spaces contained commonplace building automation technology, managers and shop stewards longed for intelligent monitoring and tracking systems to help with system maintenance, workshop cleanliness, and maker safety enhancements.

As these seven generalized themes suggest, there is much opportunity for innovation within personal fabrication spaces. Although equipment footprints and specifications often dictate layout, it is equally important to consider how a maker's interaction and movement through an environment impacts the activities they undertake. Thus far, our interactions with the built environments within which we design and fabricate are primitive: our presence turns the lights on and off, we sit and work where the stools and tables dictate, we scavenge for tools and retrieve whichever are available, and we set and reset each piece of equipment to the parameters we need. Rather than adapt our processes and projects to the environment and its contents as we do now, personal fabrication environments should continually and dynamically adapt to the practices we wish to undertake and the needs and requirements of our projects. If we could offload a number of the menial activities to personal fabrication environments, we would be free to concentrate on the activities that we enjoy or techniques or processes that require higher-levels of attention or cognitive processing.

4 HYBRID WORKSHOPS

As illustrated via the observational sessions, many environmental factors can help and hinder personal fabrication. If designers, engineers, technologists, researchers, and architects are to transform the spaces where personal fabrication occurs, such that they are in service of makers' needs, a new vision is needed. While some of the challenges that were observed with workshops today could be addressed with better signage, workshop policies, educational processes, and so on, we advocate that the integration of various types of technology could lessen some of the challenges or enhance some of the practices and workflows that we observed. Based on the practices and challenges that were reported, the workshops of the future need to be designed in service of the dynamically changing needs of makers and their projects. Such spaces will need to facilitate and encourage the flow of activities across (digital) technology and (physical) equipment divides and do so in manners that can satisfy the task, environment, and project requirements of all makers within a space. We thus envision that personal fabrication spaces will transform into what we term *hybrid workshops*.

Hybrid workshops are spaces and environments that leverage varying degrees of computation and responsive architecture to enhance design and fabrication processes and workflows. They could exist within a dedicated environment, such as is commonplace today, or become integrated within existing multi-purpose spaces. They should continue to support makers working individually or with other makers to create artifacts, and also support makers working hand in hand with intelligent surfaces, tools, and fixtures within the space. Instead of requiring makers to use tools, surfaces, workflows and processes that are dictated and designed by others, the environment should utilize as much or little actuation, autonomy, and feedback as necessary to create a space that is personalized to its occupants. It should intelligently guide makers towards equipment, practices, workflows, or processes that encourage skill development and serendipitous exploration, tailoring assistance based on project requirements and makers' current and desired skill sets. Visualization and tracking techniques should be integrated within tools and machines to impart equipment and material literacy and provide on-demand, expert assistance, as necessary. By integrating various degrees of implicit sensing, contextual understanding, and an awareness of the activities, tools, materials, and skill levels at hand, such spaces should seamlessly combine traditional analogue techniques, the rich behaviors found in workshops today, and novel digital equipment and processes to assist makers in developing, iterating on, and fabricating their designs.

Given that the amount of assistance and augmentation that is possible with technology falls on an ever-elongating continuum, hybrid workshops could take many forms. One the one hand, they could resemble the traditional workshops that we see today, including workbenches, material and project storage, and digital and traditional fabrication tools, along with a few basic sensing modules to monitor, for example, equipment usage. At this end of the spectrum, a space would be largely analog, with minimal intervention and assistance available to occupants and likely best suited for experienced makers who require or would seek little assistance. On the other hand, a hybrid workshop could also be a technology-heavy space, with technology, sensing, and actuation capabilities that record and analyze every occupant's and machine's movements, anticipating and reacting to the ever-changing context as an active part of a maker's fabrication process. This diametric instantiation of a hybrid workshop could be best suited for teaching or learning environments, where novice or young makers require step-by-step assistance and monitoring to complete an artifact. This other end of the spectrum, while not possible today from a technical standpoint, provides an extreme vision of what could be possible within the next generation of workshops, if desired.

To further explore the possibilities that hybrid workshops could afford, two design fictions present examples of individual and collaborative workflows that could be possible with the most extreme versions of hybrid workshops. This is then followed by an articulation of the technical facets and interaction challenges that such assistive spaces would need to overcome. The section concludes with an examination of four philosophical themes that will require thought and discourse if such workshops are to become commonplace.

4.1 Two Fictional Realizations of Hybrid Workshops

To illustrate how makers might work within a hybrid workshop in the future, two fictional realizations, are presented. The first explores how personalized technology, a responsive workbench, intelligent and locatable tools, and contextually-aware simulations and information, could combine with traditional processes to help a maker achieve their goals. The second explores a multi-maker scenario via dynamic facades, external inspiration, personalized tools, and adaptive mechanisms to enable individual and collaborative tasks. Such inspirational realizations explore two potential, yet extreme, versions of how the environment could become a supportive, yet collaborative aspect of personal fabrication. Note, however, that these realizations are inspirational examples and many other variants and instantiations of Hybrid Workshops, with varying degrees of personalization and assistance, are of course possible as well.

4.1.1 The Digital Botanist: Ellis

Ellis is researching new vessel shapes to improve the yields of hydroponic tomatoes. To date, none of the computer-generated models from her generative programs have improved the yield, so Ellis has decided to go back to basics, forming a new vessel by hand.

Ellis walks to the dynamic workbench in her living room and takes out her digital clay. As she is handbuilding with the clay, she begins making small coils out of clay and winding them on themselves using her fingers. She soon realizes that the coiling process produces a winded shape that may be the key to a better vessel, yet the computer-generated models that she was working on her tablet have not explored any coil-style shapes! She then begins using her hands to create a vessel using interlocking, coiled, Mobius-strips. Her workbench, which has been 3D scanning the clay form as she handbuilds, has run some simulations on its stability and cross referenced the results with a database of other artifacts that have been built using the same clay. The workbench's software has anticipated that some segments of the clay will not support themselves while the clay is still workable, so it extends tubular protrusions out of its surface, towards the bottom of her structure, to provide support while she continues to coil and sculpt.

As Ellis smooths over the clay with her fingers, she notices that her fingernails accidently leave small slashes in the clay. She realizes that the resulting shapes would be the perfect cavities to encourage more airflow into the roots of the tomato plants. She picks up a small dental pick she often uses for sculpting off her workbench to replicate the shapes, but soon realizes that a larger tool would be more useful. She notices that a screwdriver she left on her workbench is within reach, and even though it isn't the right tool, decides to use it anyway. As she grasps its handle, the texture on the grip becomes rough, and she is discouraged from using it. As she looks around her living room to see if she has a better tool to use, the augmented headset she is wearing virtually displays effectiveness metrics next to all the gribable objects that she sees. She soon sees a spatula with a high effectiveness score on her kitchen counter, walks over to the spatula, and brings it back to her workbench to carve the air cavities.

After finishing the air cavities, she gestures around the clay to lock it into place and, as her hands are dirty, verbally tells her headset to create and show her a virtual 3D model of the clay form. She is very proud of her design and decides it is good enough to share with her colleagues. She then verbally informs her headset to consult the organic biology database to determine if her design could meet FDA requirements for hydroponic food yields, and then verbally instructs her headset to alert her research team that she has a new design to discuss.

4.1.2 The Data-Driven Inventors: Nixon and Hunter

Nixon and Hunter are working on a science fair project to explore the impact of nozzle shapes on the dispersion of anti-bacterial soap within the multi-use fabrication lab in their condo building. As they will be making prototypes and dispersing particles into the air, once Nixon and Hunter enter the lab, the lab identifies them and based on the artifacts they have made the last few times they were in the space, robotic arms begin constructing a transparent, temporary yurt-like structure around two desks near the air compressor that is in the space. As Hunter and Nixon's work is often quite messy, the lab determined that this space would lead to the least contamination of others' work areas but will still allow Hunter and Nixon to work collaboratively to design new nozzles.

Hunter and Nixon step inside the yurt and get to work. Nixon pulls out his tablet to review data from the previous day's tests with foam and 3D printed nozzles, while Hunter chooses and retrieves some plastic sheeting and a hot knife from a nearby cabinet. Nixon quickly tires of analyzing yesterday's failed designs and starts looking around the room. As he glances towards a wall, he tells it to show him what his friends are working on in their nearby makerspaces. The wall then transitions to display portholes into his friend's fabrication spaces and environments. While watching the activities occurring in other labs, he notices that the haphazard layout of the portholes themselves are arranged in a web-like pattern and realizes that a similar shape might make a good nozzle design.

As Nixon sketches new designs on his tablet with his finger, Hunter sees projections of Nixon's sketches on her desk and begins to construct a prototype nozzle. To cut out the nozzle, she uses her hot knife and follows a projected line that appears on the plastic sheeting she retrieved earlier. As she has not used a hot knife in a while, her hands begin to tremble. Her hot knife detects the trembling and begins to gradually steady itself to create cleaner cuts in the plastic sheet. Once the nozzle shape is cut out, she creases and forms it with her hands, and inserts it into the air compressor hose on their desk. Nixon quickly realizes that Hunter is going to begin shooting soap everywhere, so he verbally tells his desk to put up an air curtain around him using the air vents embedded in the floor. The temporary air curtain will let Nixon watch Hunter's progress and divert soap away from his desk so he, and his tablet, do not get sticky.

Hunter runs her new nozzle through a battery of dispersion tests while Nixon looks at the real-time results on his tablet. Nixon notices the pressure in some areas of the nozzle tip is too high, so he annotates his sketch with his finger to reflect areas where new notches could be useful. While looking across the curtain, Hunter notices he is scribbling away, so she consults the updated projection of his sketch and realizes they need to make some modifications. She detaches her nozzle, grabs her hot knife, and slides her chair over to Nixon. Together, they discuss and make new incisions in the nozzle. Hunter then rolls back to her testing equipment and runs the test sequence again by tapping her soapy fingers on her desk. Nixon gives her a thumbs up, letting her know the data is already showing marked improvements.

4.1.3 Reflection

Although these scenarios both require sensing, monitoring, and technology that is not available today, they illustrate how our interactions with digitally-enhanced environments like a hybrid workshop could enhance some, but not all, aspects of design and fabrication activities.

One interesting facet is the seamless workflows that resulted across digital and physical equipment and materials. Ellis used a traditional method for design, i.e., handbuilding, guided by personal intuition and inquiry, while Nixon used digital technology but drew inspiration from dynamic, physical elements in the space around him (O5). In the case of Ellis, her intuition allowed for the creation of a design that was not possible via algorithms and computational intelligence but required her hands-on experience and expertise. The fluid use of physical and digital technology also continued throughout fabrication, which occurred in the same physical location as the design process in both scenarios, but in the case of Nixon and Hunter, was temporarily sub-divided (O1). The air curtain allowed Hunter and Nixon to continue to work together on the project, with one analyzing data and the other running test equipment but did not create an impenetrable communication or collaboration boundary between them.

The use of intelligent tools and fixtures by Hunter and Ellis exemplified how dynamic environments, intelligent tools, and materials that react in a personalized manner can enrich some, but not all, aspects of personal fabrication (O4). The ability for Ellis' workbench to anticipate a potential failure (i.e., her clay form not being able to support itself; O4) and create support protuberances and the ability of Hunter's knife to adapt to her tremors (O4) was made possible by the contextually-aware environment monitoring and interaction that was present in both locations (O7). Ellis' environment's ability to track and locate tools was also helpful, even though she was the only maker in the space contributing to the flux of tools (O2). The Hunter and Nixon scenario also illustrated how environment monitoring could mediate multi-maker, multi-agent environments to allow both makers to work together and individually (i.e., the transparent air curtain that we created between them; O1, O6) and minimize distractions and disruptions to others in the environment (i.e., the construction of Hunter/Nixon's yurt; O1, O3).

Environments enriched with actuation and just-in-time dynamicism require techniques to interact and control such technologies (O3). In these manifestations, control was exerted via voice input and gestures, to overcome limitations caused by Ellis' dirty hands and Nixon working with his tablet (O3). Other interaction techniques and modalities, would, of course, be required for different projects and environmental conditions.

While the scenarios illustrate potential avenues along which interactions with hybrid workshops could positively influence personal fabrication, hybrid workshops are not a silver bullet. No amount of intelligence or augmented feedback will replace the satisfaction that comes from creating an artifact by manipulating materials using one's own hands. There will always be benefits to working with raw materials, serendipitously discovering new forms or processes, or honing one's skills. While it could be useful for an environment to alert makers as to where their tools are or create temporary barriers to reduce distractions for others, one cannot forget that such spaces are for the maker and should be supported by as few or many technological interventions as the maker deems appropriate.

4.2 Technical Innovations Required for Hybrid Workshops

As suggested by the findings from the observational sessions, workshops are dynamic, unique spaces, each serving different populations of occupants who all have different goals, skill sets, and so on. In what follows, the five most pressing technological and interaction challenges that would be needed to make a fully assistive, automated space are detailed, along with a discussion of concerns to be mindful of when designing or implementing a Hybrid Workshop. We note that, because not all users and workspaces may desire the same level of environmental intelligence and responsiveness, the degree to which each of these technical necessities should to be overcome will vary.

4.2.1 Dynamic Facades, Spaces, and Surfaces

The observational sessions underscored how the spatial layout of a space influences the collaboration, design, and fabrication efforts of occupants (O1, O3). As many of the irritants in the workshops of today were the result of occupants needing distinct spaces for different tasks, the ability for makers to initiate, work within, and break down temporary structures or spaces to meet their project needs would be a welcome innovation, but a major technical challenge. Dynamic facades and techniques from kinetic architecture [53, 84, 108] could lessen some of the irritating situations that were observed. If the Mold Making Studio had an awareness of the noise generated by the occupant who was trying to settle their concrete, for example, it could have assisted the annoyed occupant by creating a temporary noise shelter around them, rather than the occupant having to move to a new location. As some occupants will prefer to work openly, sharing information or creatively exploring solutions with other makers, not all makers may desire to create barriers between themselves and others. Hybrid workshops will need to develop methods to ensure project, health, and safety requirements are met, while also attending to the collaborative and inspirational needs of the rest of the occupants within a space.

On a more micro level, dynamic surfaces will also be useful when project requirements are complex or unusual. Rather than, as we observed, users having to act as "muscle" in the Architecture Model Studio because custom shims are required, or having to develop ad-hoc laminating solutions with milk crates as was done in the First-Year Teaching Shop, workbenches within a hybrid workshop should have the ability to modify individual surfaces and equipment to accommodate the needs of a project (O4). If the environment itself could, for example, push, retract, or lower tools on a pegboard based on the current task, or raise or lower different portions of a workbench for clamping and support, hybrid environments would enable the space around an occupant to act as an active, rather than passive, participant in the fabrication process.

To realize each of these aspects of a hybrid workshop, innovation will be needed in terms of the actuation methods that are available for large and small-scale movement and orientation (e.g., moving or creating temporary walls), in addition to smaller, more localized actuation techniques (e.g., transforming subsections of a workbench). The methods a maker has available to them to understand, choose, and control the transformations that could occur, or dismiss potential transformations all together, will also be important.

4.2.2 Reactive, Personalized Tools

If hybrid workshops are to be in service of their occupants, they will need to actuate and reconfigure the tools occupants use to meet the ergonomic needs of a maker or the demands of the current context or project (O4). Future tools will need to be reconfigurable or 'just-in-time' and will need to take many forms, from modular tool systems that can reconfigure end effectors (e.g., to help the occupants who didn't have the correct chisels or sandpaper in the Mold Making Studio and First-Year Teaching Shop) to reusable materials that could be reformed as needed (e.g., for the First-Year Teaching Shop occupant whose space didn't have the laminate they desired). When combined with occupant monitoring and usage data, the tools in hybrid workshops will need to adapt to each maker (e.g., tool handles become smaller or larger to eliminate tremors or jittering while in use). Tools that automatically level, mediate speed and force, or create guides for a maker are already available in the marketplace [10], however workshops with personalized tools will also need to set parameters based on the current step to guide novice or distracted users [96] and the ability to revert back to their non-assistive states to enable the serendipitous practices and techniques supported by tools today.

How a maker learns to use a tool, how they change and revert tools back to their non-reactive states, the sensing and power required to achieve such personalization, and the materials required to create such tools or attachments remain immense technical challenges.

4.2.3 Tracking, Localization, and Awareness

If hybrid workshops are to be personalized to a given maker or group of makers, they need to have an awareness of the makers, materials, tools, and machinery contained within them, in addition to the tasks being performed, and the amount of automation and aid that each individual maker desires (O2, O4, O7). This will require databases of tool, material, and equipment specifications and classification and learning algorithms to detect, identify, and track equipment and tools as they are relocated throughout a space, monitor and detect equipment failures and malfunctions, identify users and learn their skill sets, identify the materials being used and classify the tasks being performed, dynamically allocate space and tasks based on the current makers and state of the workshop, and determine the sensors and methods to use given the current environmental state of the workshop (e.g., high noise levels, multiple makers, air quality, and so on). Localization technology, for example, could have benefitted the occupant in the Architecture Model Studio who was observed moving from machine to machine and had trouble keeping track of all of their tools and belongings.

Although fully assistive, smart environments have long been the vision of ubiquitous computing, and some such solutions are already being developed, e.g., sensing-bot for air quality [72], such spaces have yet to become a reality. This is especially true within the context of a workshop environment, where the multitude of tools, equipment, materials, remnants, and occupants make the task of identifying and tracking entities within a space is very difficult. In some cases, this is due to the sheer volume of equipment, tools, and materials in the space (and the occlusions they introduce), whereas in others this may be because materials or tools are visually indistinguishable. Projects such as the Smart Makerspace [52], and advancements in sensing modules and identification algorithms, however, provide hope that the integration of some (or all facets) of a fully assistive workshop environment may soon become a reality, even for environments that have space or funding limitations.

To offer full personalization, there is also a necessity for hybrid workshops to have an understanding of a maker's design and fabrication intent. While an online tutorial may provide some clues, hybrid workshops will need systems and software that is able to account for mistakes during the fabrication process or serendipitous design variants to be created [57]. When a maker does not have a pre-defined set of steps they wish to follow, the extraction of design intent from a (poorly) drawn sketch or computer model and transformation of the design into a series of comprehensive fabrication steps will be required. As we observed in almost all workshops, makers frequently changed their design throughout their fabrication activities. Methods to visualize and optimize the multitude of possible processes and equipment one could use during an ever-changing fabrication process will be required [57], in addition to techniques to adjust the design or generated steps on-demand.

When an awareness of the current design, activities being performed, and a maker's safety certifications or past accidents are available, hybrid workshops could enable for a new class of safety protocols or process workflows. For example, workspaces could hide tools that the maker is not allowed to use, hide those tools that are inappropriate for the task at hand, highlight or emphasize tools which may produce better outcomes, or automatically set a piece of equipment to the parameters that are necessary to complete a maker's next task. This will not only serve to ensure that tools and equipment are used correctly, but also increase the likelihood of artifact fabrication success.

4.2.4 Externalized Assistance and Inspiration

Many of the practices and resulting challenges that were uncovered related to a lack of understanding and knowledge on the part of makers (O1, O5, O6). Although the onus currently falls on makers to develop their own material, tool, and equipment literacy, as we observed, in many cases makers don't ask for help, or only ask for help after they have made a mistake (e.g., comments made by shop stewards in the Industrial Design Studio). This is one area where some aspects of a hybrid workshop could be useful. By combining online resources and tutorials with the rich information that can be observed from occupants moving about the space and working with various tools and equipment, hybrid workshops could provide just-in-time suggestions or display maker-specific, relevant video tutorials or visual overlays. If information about the history and practices within a given space can be combined with the collectively distributed knowledge that is held by all occupants of a space, hybrid workshops could provide aid and troubleshooting suggestions, even when only a single maker is occupying a space. Such techniques would have been useful to the occupant in the Digital Fabrication Studio who was afraid to ask others for help due to the perceived "seriousness" of the space they were in.

Further to this, there is a need to create tutorials, instruction manuals, and virtual assistants that are able to adapt to the currently available set of tools and materials, deviate from the end goal so that makers can integrate spontaneity and personality into designs, and scale to multiple makers working collaboratively [5, 32, 57]. Such methods of transferring and teaching knowledge and skills would benefit from augmented reality headsets or on-demand displays that show contextual, in-situ information and images overtop a material or next to a machine. This is similar to the 'Plastic' sign that was on the bandsaw in the Industrial Design Studio and the labels on the grinder in the Wax Studio. Such technology could also be used in combination with simulations to illustrate how or when others in the space have had success or failure with a given machine or technique or visualize the propagation of a mistake throughout the rest of a design.

Aside from imparting knowledge, hybrid workshops could also provide more advanced forms of assistance. As many makers during our sessions were observed carrying piles of materials and tools back and forth (O1; occupant in the Architecture Model Studio), a necessity of any hybrid workshop will be to utilize methods to trolley, levitate, fly, or ferry equipment to new locations as needed, possibly via drones, autonomous trolleys, or autonomous forklifts. Robotic arms could be repurposed to act as third hands, holding tools or performing repetitive tasks too tedious for human patience. Drones outfitted with projectors could display guides and blueprints over complex forms or project finished renderings over works-in-progress as a maker moves from machine to machine, negating the need for a maker to carry paper drawings with them, unlike the behavior currently exhibited in the Metal Shop and First-Year Teaching Shop. As a hybrid workshop would have an awareness of the contents and history of the entire space, this knowledge could be utilized to create visual or haptic histories of works in progress or abandoned artifacts that are left in the space (O6). This would not only serve as another medium of inspiration for makers, as project shelves do today, but also impart tacit knowledge via augmented means.

4.2.5 Environmentally-Appropriate Visualizations and Notifications

One of the most difficult challenges facing the development of the hybrid workshop will be to develop techniques to view and dismiss the information that is available to makers. Whether it be project plans and tutorials, information about the current state of tools, how certain machines should be used, feedback to guide a process, or material details, it will be difficult to determine how to present such information to makers, the amount of information that should be presented, and when such information is presented (O6). Given that traditional workshops are loud and often littered with debris (e.g., comments and observations from the First-Year Teaching Shop), most tasks require concentration and attention for safety reasons, there will thus need to be notification techniques that are alerting, yet non-intrusive for safety reasons, and informative, yet peripheral to prevent unnecessary breaks in flow. As mentioned, the use of on-body or in-situ projections or headsets may help reduce some of the visual clutter found in and around equipment, while still providing the crucial information that makers need.

When coupled with each maker's desire for personalized information, likely on a moment's notice, any visualizations or notifications will need to be summoned, read, and dismissed quickly. As many tasks require the use of both hands, there are limited modalities available for feedback in a workshop setting. Of course, it is also important to develop environmentally-appropriate interaction techniques that enable makers to share information with others in the environment or correct it when it is irrelevant or inappropriate.

4.2.6 Hybrid Workshop Design and Implementation Concerns

The integration of any new technology within a space, especially spaces as dynamic and active as workshops, does not come without a number of concerns. First, given the amount of flux and occupant movement that naturally occurs within spaces, careful attention must be given to how such technology and intelligence is integrated. Many of today's smart or internet of things devices are mounted on walls or ceilings, placed on tables or flat surfaces, or integrated within an object itself. As occupants naturally move materials, workbenches, and equipment throughout a space, mounted devices will need to be located such that they do not become obstructed and do not interfere with newly relocated projects or equipment. If all the surfaces and fixtures in a space dynamically adapt to the current activities or makers, mobile smart devices will also need to be relocated with ease, adapt the information they record to their new location within a space, and dynamically integrate recorded information into the spatial models of the environment. Sensing devices that can be attached to tools or equipment will also need to ensure that they do not introduce additional safety concerns or frustrations as a by-product of their integration (e.g., dangling cables or wires, additional weight to a device, restricted fields of view, and so on).

There are also concerns about the data that is recorded by the space itself. If a hybrid workshop has a record of the activity within a space, it also has a fine-grained record of the workflows, tools, and materials manipulated by each individual occupant. It will thus be important for such spaces to allow current and past occupants to remove their workflows at a later date and give them access to their data, similar to the General Data Protection Regulation (EU) 2016/679 [91]. As some of the workshops in the observational sessions were also found to be used for commercial purposes (i.e., a startup working on a version one prototype) and some occupants may not desire for their movements and equipment usage to be tracked or integrated within the intelligence and history of a space, hybrid workshops will also need to ensure that the techniques they use for detection, identification, and tracking enable occupants to opt out of them, or their projects, being tracked. Implementing such functionality will be a difficult task for vision-based identification techniques or machine learning algorithms that utilize aggregated tool, equipment, or material usage for classification and learning.

Regardless of the amount of assistance that is desired by the occupants of a hybrid workshop, budgetary concerns will always be an important factor impacting the implementation of a workshop. The costs associated with creating and maintaining a makerspace vary greatly: from low budget community-run spaces like the Multi-Use Makerspace, where all equipment is donated, to medium to high budget spaces that have dedicated staff, equipment contracts, and yearly budgets, such as the Rapid Prototyping Center. If every tool, material, and piece of equipment is "intelligent" then not only will the startup costs of these entities be increased, but so too will the costs associated with their upkeep, repair, and replacement. Although the Makerspace Playbook [68] and Maker's Manual [110] already suggest that spaces should budget for long term care and maintenance, it will be equally important to consider the compatibility costs of new intelligent tools and fixtures that become available, the amount of data that each new device will need to record so it can be used within the machine learning algorithms employed in a space, and the costs associated with upgrading or creating new classification and learning algorithms as the tasks performed within a space change over time.

As the degree of assistance and intelligence available within workshops today is very far from the guidance and help that could potentially be offered by a Hybrid Workshop, there are many avenues along which next steps could be taken. Of course, continuing to improve activity recognition techniques and miniaturizing sensors so they can form the backbone of an intelligent, hybrid workshop will be fruitful, however, in the short term, it may be best to focus on smaller innovations that could benefit as many occupants as possible. This could come in the form of tool-based assistance, as tools form the basis of many fabrication tasks and currently impose one of the largest challenges to occupants. For example, the use of QR codes or motion tracking markers would allow equipment and simple hand tools to be located within a space or safety information to be dynamically displayed near equipment and tools via head-mounted displays. This would immediately help decrease the frustration that many occupants expressed during the observational sessions and promote safer workflows. Similarly, continuing work on guidance-based tools and equipment, such as Drill Sargent [96], will increase safe practices, but also have the benefit of increasing process knowledge – two tenets that were of concern to occupants and shop stewards. Once many of the tool-based challenges are overcome, developing solutions to enhance makers' interactions with surfaces, machines, and materials will be a worthwhile next step, as will more global challenges that relate to the allocation and creation of space and territory, the summoning or dismissal of technology and assistance, and external inspiration.

4.3 Philosophical Challenges Posed by Hybrid Workshops

Although hybrid workshops could come in many forms and the degree of technical innovation desired will vary, the very notion of such workshops brings about many philosophical themes and questions that require discourse and contemplation.

4.3.1 Augmentation of Self Versus Space

At their extreme, hybrid workshops could require a level of awareness that cannot be deduced without intelligent sensing systems. Thus, it is important to explore the location and degree of sensing that is required. In the workshops we visited that had environmental sensing, all hardware and sensing systems were installed in the environment itself, within the walls, ceiling, or electrical systems. Such systems provide macro levels of detail about a space and can help a manager deduce the general state of the environment. Although the most popular, this location and degree of sensing is not the only option. Research projects such as the Smart MakerSpace [52] and Drill Sargent [96] have shown that sensing and a higher level of awareness can be integrated and deduced directly within the safety glasses or hand tools one is using. This micro level of instrumentation can provide contextual-information and detail that could be specialized to each make and model of tool or machine that is present in the space – information which would be difficult to deduce from a generalized-environmental system. Other work and products, such as that from Campbell et al. [22] and the Daqri headset [23] have suggested that makers themselves be augmented with intelligent sensing. The augmentation of individual makers would allow for increased privacy throughout the space, in addition to putting the maker in direct control of the level of assistance they wish to have via the sensors that they choose to wear.

Thus, two outstanding questions to consider are: (i) To what degree do we augment the environment, augment the tools and machine, augment the maker, or augment all entities in a space and (ii) how do we fluidly transition between various levels of augmentation and the information and awareness they can provide?

4.3.2 Agency with Reactive, Adaptive Environments (and Tools and Materials)

A necessity of any instantiation of a hybrid workshop will be the ability to support however little or much external assistance, automation, and intelligence that a maker may want. This of course comes with the added challenge of determining how, and the degree to which, a maker can modify the environment around them (in addition to its contents). Considering the dynamically changing environmental demands they find themselves in, the use of one modality may be sufficient at one moment, but inadequate in the next. For example, modalities such as touch or voice may work in certain conditions, however task demands may require makers to switch between multiple modalities as noise levels and cleanliness in the environment changes [40].

The relationships we have with the tools, materials, and other occupants in the environment, in addition to their visual representations [41], will dictate how we view and choose to interact with the elements in our personal fabrication environments. If a tool is viewed as a passive accessory or a machine that performs one dedicated function, we may be more likely to view it as a subordinate and something we should be able to take complete control over. Alternatively, for equipment that can be used by multiple makers at once or equipment that is multi-purpose, we may feel less able to customize it to our needs, and thus use primitive methods to exert minimal control.

Given these constraints, it is important to consider what metaphors and modalities are most appropriate for controlling different environmental entities and what implications these metaphors will have on the degree of control we feel we can exert over the environment and our own fabrication activities. Further, when exerting control over a space or tool, when conflicts arise due to competing interests from multiple makers, how are they resolved? It could be appropriate for the environment to dynamically determine which maker (or group of makers) are most important, however, this may lead to frustration and biasing if the mechanisms by which decisions are made are not transparent.

4.3.3 Environments as Collaborators and Co-Creators

The observations illustrated many ways workshops already act as implicit participants during personal fabrication. As design and fabrication will continue to become ever more intertwined with the environments around us, we will need to consider the degree to which we want an environment to be an active participant and co-creator. Purists believe that digital tools should only be used for modelling or experiments that are difficult to evaluate using traditional techniques [88]. Others embrace notions of automation, believing that makers will transition into roles where they are the identifiers and specifiers of problems, with the end-to-end process of creating designs and products being performed by an assembly line of robots and machines [7]. These views challenge the very notion of personal fabrication. In some cases, a human's own cognition and physical actions result in an artifact, while in others the artifact results from an initial human idea, with the virtual and mechanical entities simply creating a manifestation of it. This raises important questions about the authenticity of such collaborative relationships and artifacts: e.g., Are such fabricated artifacts authentic? Does the pride garnered from imagining a form equate to building it?

More generally, this leads to questions that makers will have to ask themselves before, during, and after the creation of an artifact. Essentially, at which point does fabrication transition from being a craft that inundates a maker with feelings of pride and accomplishment, to an automated, mechanical process? When environments, fixtures, tools, and materials are co-creators, where does the role of the human stop and that of the machine begin?

4.3.4 Environment-Free Personal Fabrication

In the current proposal of hybrid workshops, the locations where personal fabrication occurs are constrained to a space or environment that has the equipment, materials, and tools dedicated to such tasks. As fabrication activities become more agile and equipment becomes more compact and mobile [49, 54, 73, 93], we will continue to move closer to Gershefeld's vision where "*anyone can make anything, anywhere*" [35]. If varying degrees of personal fabrication can be supported, regardless of the environmental context, it will be crucial to consider, if, and how, we should transition between dedicated, fully-fledged fabrication spaces, and spaces where little to no design and fabrication equipment or processes are supported. Current techniques to transition between the use of smart watches, smart phones, tablets, and desktop computers restrict the software features that are available via sensing techniques and the screen real-estate on a given device [29]. While it may be appropriate to restrict the available types of 3D printing methods based on the current environmental context, for example, such techniques may not scale to all types of equipment or allow for graceful transitions between extreme settings.

As such, it is important to not only build an understanding of how different activities can be accomplished when equipment, tools, and materials will differ, but also determine how to design the very tools, techniques, and processes that are used for personal fabrication. They should be designed such that they can meet the vast desires of makers while ensuring that they are versatile to environmental conditions and the transitions between these conditions.

5 CONCLUSION

Although personal fabrication has seen increased attention, adoption, and research over the last decade, there is still a great deal that is unknown about the role that the spaces in which makers design and fabricate have on the artifacts they create and experiences they encounter during fabrication. As environments and tools continue to become aware, intelligent, and mobile, it will be important to have a foundational understanding of the practices that occur in workshops today. Inspired by the ever-changing environments that we fabricate within, this work recast foci towards the role and impact that the *spaces* where fabrication occurs have on ideation, design, and prototyping processes.

This work reported on in-situ observational sessions that were conducted at eleven North American makerspaces, fabrication studios, and workshops, in addition to informal interviews with makers. The sessions and interviews underscored the numerous challenges and rich practices that are found in the workshops of today. They highlighted the difficulties and opportunities that physical spatial barriers, organizational flux, inadequate tools and equipment, distributed knowledge and inspiration, agency issues and territoriality behaviors, and limited environmental monitoring can have on the processes makers use and the experiences they have while designing and fabricating.

These observations led to the notion that the next generation of workshops, i.e., *hybrid workshops*, could benefit from the use of intelligent sensing and levels of awareness about the state of makers, tools, materials, and equipment to ensure that makers are supported during design and fabrication activities. By diving deeper into the technical and philosophical challenges that adaptive, personalized workspaces will pose, the work illustrated that many research avenues have yet to be explored. This work should serve not only to recast focus on the increasingly important role that the environment has on design and fabrication, but also to encourage discourse on how to best encourage and bootstrap the rich workflows and practices that are found in fabrication environments today and how to lessen many of the challenges fabrication spaces themselves pose to makers in the 21st century and beyond.

REFERENCES

[1] Access Engineering. 2015. *Making a Makerspace? Guidelines for Accessibility and Universal Design.* Accessed August 2017, https://www.washington.edu/doit/sites/default/files/atoms/files/Making_a_Makerspace_8_03_15.pdf.

[2] Harshit Agrawal, Udayan Umapathi, Robert Kovacs, Johannes Frohnhofen, Hsiang-Ting Chen, Stefanie Mueller, and Patrick Baudisch. 2015. Protopiper: Physically Sketching Room-Sized Objects at Actual Scale. In *Proceedings of the ACM Symposium on User Interface Software & Technology*, 427-436. http://dx.doi.org/10.1145/2807442.2807505

[3] Kristina Andersen. 2014. The deliberate cargo cult. In *Proceedings of the Conference on Designing Interactive Systems*, 627-636. http://dx.doi.org/10.1145/2598510.2598596

[4] Chris Anderson. 2012. *Makers: The New Industrial Revolution.* Crown Business Books, Massachusetts.

[5] Stavros Antifakos, Florian Michahelles, and Bernt Schiele. 2002. Proactive Instructions for Furniture Assembly. In *Proceedings of the International Conference on Ubiquitous Computing*, 351-360. http://dx.doi.org/10.1007/3-540-45809-3_27

[6] Till Ballendat, Nicolai Marquardt, and Saul Greenberg. 2010. Proxemic Interaction: Designing for a Proximity and Orientation-Aware Environment. In *Proceedings of the International Conference on Interactive Tabletops and Surfaces*, 121–130. http://doi.org/10.1145/1936652.1936676

[7] Francois Barbier. June 2017. *5 trends for the future of manufacturing.* https://www.weforum.org/agenda/2017/06/what-s-going-on-with-manufacturing-b013f435-1746-4bce-ac75-05c642652d42/. Retrieved October 2017.

[8] Jeffrey Bardzell, Shaowen Bardzell, and Austin Toombs. 2014. "Now That's Definitely a Proper Hack": Self-Made Tools in Hackerspaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems,* 473-476. http://dx.doi.org/10.1145/2556288.2557221

[9] Gilles Bailly, Sidharth Sahdev, Sylvain Malacria, and Thomas Pietrzak. 2016. Livingdesktop: Augmenting Desktop Workstation with Actuated Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 5298-5310. https://doi.org/10.1145/2858036.2858208

[10] *Black+Decker SMARTTECH Products.* (n.d.). http://www.blackanddecker.com/en-us/products/smartech. Accessed August 2016.

[11] Henriette H. Bier. 2011. Robotic Environments. In *Proceedings of the 28th International Symposium on Automation and Robotics in Construction.* http://dx.doi.org/ 10.22260/ISARC2011/0160

[12] Matthew Blackshaw, Anthony devincenzi, David Lakatos, Daniel Leithinger, and Hiroshi Ishii. 2011. Recompose: Direct and Gestural Interaction with an Actuated Surface. In *Extended Abstracts on Human Factors in Computing Systems*, 1237-1242. http://dx.doi.org/10.1145/2048259.2048272

[13] Paulo Blikstein. 2013. Digital Fabrication and 'Making' In Education: The Democratization of Invention. *Fablabs: of Machines, Makers and Inventors*, 1-21.

[14] Olha Bondarenko and R. Janssen. 2005. Documents at Hand: Learning from Paper to Improve Digital Technologies. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*: 121–130. http://doi.org/10.1.1.137.7259

[15] Adrien Bousseau, Theophanis Tsandilas, Lora Oehlberg, and Wendy E. Mackay. 2016. How Novices Sketch and Prototype Hand-Fabricated Objects. *In Proceedings of the CHI Conference on Human Factors in Computing Systems,* 397-408. http://dx.doi.org/10.1145/2858036.2858159

[16] Lauren Britton. 2012. The Makings of Maker: Making Space for Creation, Not Just Consumption. *Library Journal,* 137(16): 2023.

[17] Graham Brown. 2009. Claiming a corner at work: Measuring employee territoriality in their workspaces. *Journal of Environmental Psychology*, 29(1): 44-52. https://doi.org/10.1016/j.jenvp.2008.05.004

[18] Graham Brown and Helena Zhu. 2016. 'My workspace, not yours': The pact of psychological ownership and territoriality in organizations. *Journal of Environmental Psychology*, 48: 54-64. https://doi.org/10.1016/j.jenvp.2016.08.001

[19] Bradley A. Camburn, Karen H. Sng, K. Blake Perez, Kevin Otto, Kristin L. Wood, Daniel Jensen, and Richard Crawford. 2015. The Way Makers Prototype: Principles of DIY Design. In *Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, V007T06A004-V007T06A004. http://dx.doi.org/10.1115/DETC2015-46295

[20] Marcelo Coelho and Jamie Zigelbaum. 2011. Shape-Changing Interfaces. *Personal and Ubiquitous Computing,* 15(2): 161-173. http://dx.doi.org/10.1007/s00779-010-0311-y

[21] Irene Cole. 1982. Human Aspects of Office Filing: Implications for the Electronic Office. In *Proceedings of the Human Factors and Ergonomics Society Annual Meetings*, 59–63. http://dx.doi.org/10.1177/154193128202600115

[22] Timothy Campbell, Jonathan Harper, Björn Hartmann, and Eric Paulos. 2015. *Towards Digital Apprenticeship: Wearable Activity Recognition in the Workshop Setting*. Technical Report No. UCB/EECS-2015-172.

[23] Daqri. (n.d.). http://daqri.com. Accessed July 2016.

[24] M. Ann Garrison Darrin and Jerry A. Krill. 2016. Infusing Innovation into Organizations: A Systems Engineering Approach. CRC Press.

[25] Laura Devendorf and Kimiko Ryokai. 2014. Being the machine: Exploring New Modes of Making. In *Proceedings of the Companion Publication on Designing Interactive Systems*, 33-36. http://dx.doi.org/10.1145/2598784.2602775

[26] Linda Di Geronimo, Maria Husmann, Abhimanyu Patel, Can Tuerk, and Moira C Norrie. 2016. CTAT: Tilt-and-Tap Across Devices. In *Proceedings of the International Conference on Web Engineering*, 96–113. http://doi.org/10.1007/3-540-45144-7

[27] George W. Fitzmaurice, Azam Khan, William Buxton, Gordon Kurtenback, and Ravin Balakrishnan. 2003. Sentient Data Access via a Diverse Society of Devices. *ACM Queue* 1(8): 53–62. http://doi.org/10.1145/966712.966721

[28] Laura Fleming. 2015. Worlds of making: Best practices for establishing a makerspace for your school. Corwin Press.

[29] Murelle Florins and Jean Vanderdonckt. 2004. Graceful degradation of user interfaces as a design method for multiplatform systems. In *Proceedings of the International Conference on Intelligent User Interfaces*, 140-147. http://dx.doi.org/10.1145/964442.964469

[30] Sean Follmer, Sean, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. Inform: Dynamic Physical Affordances and Constraints Through Shape and Object Actuation. In *Proceedings of the ACM Symposium on User Interface Software and Technology*, 417-426. http://dx.doi.org/10.1145/2501988.2502032

[31] Sarah Fox, Rachel Rose Ulgado, and Daniela Rosner. 2015. Hacking Culture, Not Devices: Access and Recognition in Feminist Hackerspaces. In *Proceedings of the ACM Conference on Computer Supported Cooperative Work & Social Computing*, 56-68. http://dx.doi.org/10.1145/2675133.2675223

[32] Ailie Fraser, Tovi Grossman, and George Fitzmaurice. 2017. Webuild: Automatically Distributing Assembly Tasks Among Collocated Workers to Improve Coordination. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1817-1830. https://doi.org/10.1145/3025453.3026036

[33] Hans Gellersen, Carl Fischer, Dominique Guinard, et al. 2009. Supporting device discovery and spontaneous interaction with spatial references. *Personal and Ubiquitous Computing*, 13(4): 255–264. http://doi.org/10.1007/s00779-008-0206-3

[34] Georgi V., Georgiev, Iván Sánchez Milara, and Denzil Ferreira. 2017. A Framework for Capturing Creativity in Digital Fabrication. *The Design Journal*, 20(1): S3659-S3668. http://urn.fi/urn:nbn:fi-fe201710098936

[35] Neil Gershenfeld. 2012. How to make almost anything: The digital fabrication revolution. *Foreign Affairs*, 91: 43.

[36] David Philip Green, Verena Fuchsberger, David Kirk, Nick Taylor, David Chatting, Janis Lena Meissner, Martin Murer, Manfred Tscheligi, Silvia Lindtner, Pernille Bjorn, and Andreas Reiter. 2017. Open Design at the Intersection of Making and Manufacturing. In *Extended Abstracts of Human Factors in Computing Systems*, 542-549. https://doi.org/10.1145/3027063.3027087

[37] Jens Emil Grønbæk, Henrik Korsgaard, Marianne Graves Petersen, Morten Henriksen Birk, and Peter Gall Krogh. 2017. Proxemic Transitions: Designing Shape-Changing Furniture for Informal Meetings. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 7029-7041. http://dx.doi.org/10.1145/3025453.3025487

[38] Chris Harrison and Anind K. Dey. 2008. Lean and Zoom: Proximity-Aware User Interface and Content Magnification. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 207–510. http://doi.org/10.1145/1357054.1357135

[39] Mohammad A. Hassanain. 2010. Analysis of factors influencing office workplace planning and design in corporate facilities. *Journal of Building Appraisal*, 6(4), 183-197. https://doi.org/10.1057/jba.2010.22

[40] Seongkook Heo, Michelle Annett, Benjamin Lafreniere, Tovi Grossman, and George Fitzmaurice. 2017. No Need to Stop What You're Doing: Exploring No-Handed Smartwatch Interaction. *In Proceedings of the Graphics Interface Conference*, 107-114. https://doi.org/10.20380/GI2017.14

[41] Pamela J. Hinds, Teresa L. Roberts, and Hank Jones. 2004. Whose job is it anyway? A study of human-robot interaction in a collaborative task. *Journal of Human Computer Interaction*, 19(1), 151-181. http://dx.doi.org/10.1207/s15327051hci1901&2_7

[42] Matthew Hong, Anne Marie Piper, Nadir Weibel, Simon Olberding, and James Hollan. 2012. Microanalysis of Active Reading Behavior to Inform Design of Interactive Desktop Workspaces. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, 215–224. http://doi.org/10.1145/2396636.2396670

[43] Lara Houston, Steven J. Jackson, Daniela K. Rosner, Syed Ishtiaque Ahmed, Meg Young, and Laewoo Kang. 2016. Values in Repair. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1403-1414. https://doi.org/10.1145/2858036.2858470

[44] Nathanial Hudson, Celena Alcock, and Parmit K. Chilana. Understanding Newcomers to 3D Printing: Motivations, Workflows, and Barriers of Casual Makers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 384-396. http://dx.doi.org/10.1145/2858036.2858266

[45] Pradthana Jarusriboonchai, Thomas Olsson, Vikas Prabhu, and Kaisa Vaananen-Vainio-Mattila. 2015. Cuesense: A Wearable Proximity-Aware Display Enhancing Encounters. In *Extended Abstracts of Human Factors in Computing Systems*, 2127–2132. http://doi.org/10.1145/2702613.2732833

[46] Wendy G Ju, Brian A Lee, and Scott R Klemmer. 2007. Range - Exploring Proxemics in Collaborative Whiteboard Interaction. In *Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, 2483–2488. http://doi.org/10.1145/1240866.1241028

[47] Adam Kemp. 2013. The Makerspace Workbench: Tools, Technologies, and Techniques for Making. Maker Media, Inc.

[48] Alison Kidd. 1994. The Marks Are on The Knowledge Worker. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 186-191. http://dx.doi.org/10.1145/191666.191740

[49] Jeeeun Kim, Haruki Takahashi, Homei Miyashita, Michelle Annett, and Tom Yeh. 2017. Machines as Co-Designers: A Fiction on the Future of Human-Fabrication Machine Interaction. In *Proceedings of the SIGCHI Conference Extended Abstracts on Human Factors in Computing Systems*, 790-805. https://doi.org/10.1145/3027063.3052763

[50] David Kirsh. 1995. The Intelligent Use of Space. *Artificial Intelligence*, 73(1): 31–68. http://dx.doi.org/10.1016/0004-3702(94)00017-U

[51] Ulrike Kister, Patrick Reipschl, Fabrice Matulic, and Raimund Dachselt. 2015. Bodylenses – Embodied Magic Lenses and Personal Territories for Wall Displays. In *Proceedings of the International Conference on Interactive Tabletops and Surfaces*, 117–126. http://doi.org/10.1145/2817721.2817726

[52] Jarrod Knibbe, Tovi Grossman, and George Fitzmaurice. 2015. Smart Makerspace: An Immersive Instructional Space for Physical Tasks. In *Proceedings of the International Conference on Interactive Tabletops & Surfaces*, 83-92. http://dx.doi.org/10.1145/2817721.2817741

[53] Silika Rahman Kona and Saleh Uddin. 2006. Movement in Architecture: An Analytical Approach Towards Organic Characteristics. In *Proceedings of Communicating Space(s): 24th ecaade Conference*, 714-719.

[54] Gokul Krishnan. Designing a Mobile Makerspace for Children's Hospital Patients: Enhancing Patients' Agency and Identity in Learning. Vanderbilt University, 2015.

[55] Stacey Kuznetsov and Eric Paulos. 2010. Rise of the expert amateur: DIY projects, communities, and cultures. In *Proceedings of the Nordic Conference on Human-Computer Interaction*, 295-304. http://dx.doi.org/10.1145/1868914.1868950

[56] David Lakatos. 2012. AMPHORM: Form Giving Through Gestural Interaction to Shape Changing Objects. Massachusetts Institute of Technology.

[57] Matthew Lakier, Michelle Annett, Daniel Wigdor, 2018. Automatics: Dynamically Generating Fabrication Tasks to Adapt to Varying Contexts. *ACM Transactions on Computer-Human Interaction*, 25(4).

[58] Sophie Landwehr Sydow and Martin Jonsson. 2015. The organization of personal fabrication: Hackathons and makerspaces as semi-professional places for creative making. In *Proceedings of Critical Alternatives*.

[59] David Ledo, Saul Greenberg, Nicolai Marquardt, and Sebastian Boring. 2015. Proxemic-Aware Controls: Designing Remote Controls for Ubiquitous Computing Ecologies. In *Proceedings of the International Conference on Human-Computer Interaction with Mobile Devices & Services*, 187–198. http://doi.org/10.1145/2785830.2785871

[60] So Young Lee and Jay L. Brand. 2005. "Effects of control over office workspace on perceptions of the work environment and work outcomes." *Journal of Environmental Psychology*, 25(3): 323-333. https://doi.org/10.1016/j.jenvp.2005.08.001

[61] Anke Lehmann, Heidrun Schumann, Oliver Staadt, and Christian Tominski. 2011. Physical Navigation to Support Graph Exploration on a Large High-Resolution Display. *International Symposium on Visual Computing*, 496–507. http://doi.org/10.1007/978-3-642-24028-7_46

[62] Daniel Leithinger, David Lakatos, Anthony Devincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and gestural interaction with relief: a 2.5 D shape display. *In Proceedings of the ACM Symposium on User Interface Software and Technology*, 541-548.http://dx.doi.org/10.1145/2047196.2047268

[63] Steven Levy. 2010. Hackers: Heroes of the Computer Revolution. O'Reilly Media.

[64] Jessica Lingel. 2016. The Poetics of Socio-Technical Space: Evaluating the Internet of Things Through Craft. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 815-826. http://dx.doi.org/10.1145/2858036.2858399

[65] Thomas Ludwig, Oliver Stickel, Alexander Boden, Volkmar Pipek, and Volker Wulf. 2015. Appropriating Digital Fabrication Technologies - A comparative study of two 3D Printing Communities. In *Proceedings of the iconference*.

[66] Thomas Ludwig, Oliver Stickel, Alexander Boden, and Volkmar Pipek. 2014. Towards sociable technologies: an empirical study on designing appropriation infrastructures for 3D printing. In *Proceedings of Designing Interactive Systems*, 835-844. http://dx.doi.org/10.1145/2598510.2598528

[67] *Maker Market Study*. 2013. http://cdn.makezine.com/ make/sales /Maker-Market-Study.pdf. Accessed July 2016.

[68] *Makerspace Playbook*. 2013. http://makered.org/wp-content/uploads/2014/09/Makerspace-Playbook-Feb-2013.pdf. Accessed July 2016.

[69] Thomas W. Malone. 1983. How Do People Organize Their Desks?: Implications for The Design of Office Information Systems. *ACM Transactions on Information Systems*, 1(1): 99-112. http://dx.doi.org/10.1145/357423.357430

[70] Nicolai Marquardt, Till Ballendat, Sebastian Boring, Saul Greenberg, and Ken Hinckley. 2012. Gradual Engagement: Facilitating Information Exchange between Digital Devices as a Function of Proximity. In *Proceedings of the International Conference on Interactive Tabletops and Surfaces*, 31–40. http://doi.org/10.1145/2396636.2396642

[71] Jackie Marsh, Kristiina Kumpulainen, Bobby Nisha, Anca Velicu, Alicia Blum-Ross, David Hyatt, Svanborg R. Jónsdóttir, Rachael Levy, Sabine Little, George Marusteru, Margrét Elísabet Ólafsdóttir, Kjetil Sandvik, Fiona Scott, Klaus Thestrup, Hans Christian Arnseth, Kristín Dýrfjörð, Alfredo Jornet, Skúlína Hlíf Kjartansdóttir, Kate Pahl, Svava Pétursdóttir and Gísli Thorsteinsson. 2017. *Makerspaces in the Early Years: A Literature Review*. University of Sheffield: makey Project.

[72] Ron Martin and Agnis Stibe. 2016. Sensing-Bot and Persuasive Systems for the New Makerspace. In *ECSW@ PERSUASIVE*.

[73] Christian Mckay and Kylie Peppler. 2013. Makercart: A mobile fab lab for the classroom. In *Proceedings of the Interaction Design for Children Conference*. Position Paper.

[74] Andrew Milne, Bernhard Riecke, and Alissa Antle. 2014. Exploring Maker Practice: Common Attitudes, Habits and Skills from Vancouver's Maker Community. *Studies*, 19(21):23.

[75] Bakhtiar Mikhak, Christopher Lyon, Tim Gorton, Neil Gershenfeld, Caroline McEnnis, and Jason Taylor. 2002. Fab Lab: an alternate model of ICT for development. In *Proceedings of the International Conference on Open Collaborative Design for Sustainable Innovation*.

[76] Diane Mizrachi. 2013. Individuality and diversity among undergraduates' academic information behaviors: An exploratory study. *International Journal of Knowledge Content Development & Technology*, 3(2): 29–42. http://doi.org/10.5865/IJKCT.2013.3.2.029

[77] Stefanie Mueller, Bastian Kruck, and Patrick Baudisch. 2013. Laserorigami: laser-cutting 3D objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2585-2592. http://dx.doi.org/10.1145/2470654.2481358

[78] Ken Nakagaki, Luke Vink, Jared Counts, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2016. Materiable: Rendering Dynamic Material Properties in Response to Direct Physical Touch with Shape Changing Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2764-2772. http://dx.doi.org/10.1145/2858036.2858104

[79] Martin M. Nielsen. 2003. Representations at Work. Outlines. *Critical Practice Studies*, 5(2): 69-77.

[80] Nancy Nersessian, Wendy C. Newstetter, Elke Kurz-Milcke, and Jim Davies. 2002. A mixed-method approach to studying distributed cognition in evolving environments. In *Proceedings of the International Conference on Learning Sciences*, 307-314.

[81] Lora Oehlberg, Wesley Willett, and Wendy E. Mackay. 2015. Patterns of Physical Design Remixing in Online Maker Communities. In *Proceedings of the SIGCHI Conference on Human Factors in Computing*, 639-648. https://doi.org/10.1145/2702123.2702175

[82] Kas Oosterhuis and Nimish Biloria. 2008. Interactions with proactive architectural spaces: the muscle projects. *Communications of the ACM*, 51(6): 70-78. http://dx.doi.org/10.1145/1349026.1349041

[83] Antti Oulasvirta and Lauri Sumari. 2007. Mobile kits and laptop trays: managing multiple devices in mobile information work. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1127-1136. http://dx.doi.org/10.1145/1240624.1240795

[84] Amanda Parkes, Ivan Poupyrev, and Hiroshi Ishii. 2008. Designing kinetic interactions for organic user interfaces. *Communications of the ACM*, 51(6): 58-65. http://dx.doi.org/10.1145/1349026.1349039

[85] Irene Posch and Geraldine Fitzpatrick. 2012. First steps in the fablab: experiences engaging children. In *Proceedings of the Australian Computer-Human Interaction Conference*, 497-500. http://dx.doi.org/10.1145/2414536.2414612

[86] Irene Posch, Hideaki Ogawa, Christopher Lindinger, Roland Haring, and Horst Hörtner. 2010. Introducing the fablab as interactive exhibition space. In *Proceedings of the International Conference on Interaction Design and Children*, 254-257. http://dx.doi.org/10.1145/1810543.1810584

[87] Steven Pryor. 2014. Implementing a 3D Printing Service in an Academic Library, *Journal of Library Administration*, 54(1): 1-10. http://dx.doi.org/10.1080/01930826.2014.893110

[88] David Pye. 1968. The Nature and Art of Workmanship. A&C Black.

[89] Roman Rädle, Hans-Christian Jetter, Nicolai Marquardt, Harald Reiterer, and Yvonne Rogers. 2014. Huddlelamp: Spatially- Aware Mobile Displays for Ad-hoc Around-the-Table Collaboration. In *Proceedings of the International Conference on Interactive Tabletops and Surfaces*, 45–54. http://doi.org/10.1145/2669485.2676584

[90] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 735-744. http://dx.doi.org/10.1145/2207676.2207781

[91] *Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation) (Text with EEA relevance).* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2016:119:TOC. Accessed August 2018.

[92] Daniela Rosner and Jonathan Bean. 2009. Learning from IKEA hacking: I'm not one to decoupage a tabletop and call it a day. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 419-422. http://dx.doi.org/10.1145/1518701.1518768

[93] Thijs Roumen, Bastian Kruck, Tobias Dürschmid, Tobias Nack, and Patrick Baudisch. 2016. Mobile fabrication. In *Proceedings of the Annual Symposium on User Interface Software and Technology*, 3-14. http://dx.doi.org/10.1145/2984511.2984586

[94] Vincent F. Scalfani and Josh Sahib. 2013. A model for managing 3D printing services in academic libraries. *Issues in Science & Technology Librarianship*, 72: 1-13. http://dx.doi.org/10.5062/F4XS5SB9

[95] Holger Schnädelbach, Ainojie Irune, David Kirk, Kevin Glover, and Patrick Brundell. 2012. ExoBuilding: Physiologically Driven Adaptive Architecture. *ACM Transactions on Computer-Human Interaction*, 19(4): 25. http://dx.doi.org/ 10.1145/2395131.2395132

[96] Eldon Schoop, Michelle Nguyen, Daniel Lim, Valkyrie Savage, Sean Follmer, and Björn Hartmann. 2016. Drill Sergeant: Supporting Physical Construction Projects through an Ecosystem of Augmented Tools. In *Proceedings of the Extended Abstracts on Human Factors in Computing Systems*, 1607-1614. http://dx.doi.org/10.1145/2851581.2892429

[97] Stacey D. Scott, Carpendale Sheelagh, and Kori. M. Inkpen. 2004. Territoriality in Collaborative Tabletop Workspaces. In *Proceedings of the Conference on Computer-Supported Cooperative Work*, 294–303. http://doi.org/10.1145/1031607.1031655

[98] Abigail J Sellen and Richard HR Harper. 2003. The Myth of the Paperless Office. MIT press, Cambridge, MA, USA.

[99] Kimberly Sheridan, Erica Rosenfeld Halverson, Breanne Litts, Lisa Brahms, Lynette Jacobs-Priebe, and Trevor Owens. 2004. Learning in the making: A comparative case study of three makerspaces. *Harvard Educational Review*, 84(4): 505-531. http://dx.doi.org/10.17763/haer.84.4.brr34733723j648u

[100] Jay Silver. 2009. Awakening to maker methodology: the metamorphosis of a curious caterpillar. In *Proceedings of the International Conference on Interaction Design and Children*, 242-245. http://dx.doi.org/10.1145/1551788.1551841

[101] Diane Slatter and Zaana Howard. 2013. A Place to Make, Hack, and Learn: Makerspaces in Australian Public Libraries. *The Australian Library Journal*, 62(4): 272-284. http://dx.doi.org/10.1080/00049670.2013.853335

[102] Sowmya Somanath, Lora Oehlberg, Janette Hughes, Ehud Sharlin, and Mario Costa Sousa. 2017. 'Maker' within Constraints: Exploratory Study of Young Learners using Arduino at a High School in India. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 96-108. https://doi.org/10.1145/3025453.3025849

[103] Daniel Southwick and Matt Ratto. 2015. The Discrete Practices of 3D Printing. http://hdl.handle.net/1807/71939

[104] Tristan d'Estree Sterk. 2006. Responsive Architecture: User-Centered Interactions within the Hybridized Model of Control. In *Proceedings of the Game Set and Match II Conference*, 494-501.

[105] Anselm Strauss and Juliet Corbin. 1990. *Basics of Qualitative Research Vol 15*. Sage, Newberry Park.

[106] Kentaro Takano, Hirohito Shibata, and Junko Ichino. 2014. Microscopic analysis of document handling while reading paper documents to improve digital reading device. In *Proceedings of the Annual Meeting of the Australian Special Interest Group for Computer Human Interaction*, 559–567. http://doi.org/10.1017/CBO9781107415324.004

[107] Kentaro Takano, Hirohito Shibata, and Kengo Omura. 2015. Effects of paper on cross-reference reading for multiple documents: Comparison of reading performances and processes between paper and computer displays. In *Proceedings of the Annual Meeting of the Australian Special Interest Group for Computer Human Interaction*, 497–505. http://doi.org/10.1145/2838739.2838745

[108] Yuichiro Takeuchi. 2014. Building a World of Habitable Bits. *Interactions,* 21(6): 52-57. http://dx.doi.org/10.1145/2668903

[109] Nick Taylor, Ursula Hurley, and Philip Connolly. 2016. Making Community: The Wider Role of Makerspaces in Public Life. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1415-1425. http://dx.doi.org/10.1145/2858036.2858073

[110] *The Maker's Manual*. 2015. http://www.psfk.com/ report/makers-manual. Accessed July 2016.

[111] Katja Thoring, Roland M. Mueller, Petra Badke-Schaub, P., and Pieter Desmet. 2016. Design the Campus: Introducing a Toolkit for Developing Creative Learning Spaces. In *Proceedings of Cumulus Association International Conference*.

[112] Austin L. Toombs, Shaowen Bardzell, and Jeffrey Bardzell. 2014. Becoming makers: hackerspace member habits, values, and identities. *Journal of Peer Production*, 5.

[113] Cristen Torrey, Elizabeth F. Churchill, and David W. Mcdonald. 2009. Learning how: the search for craft knowledge on the internet. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1371-1380. http://dx.doi.org/10.1145/1518701.1518908

[114] Daniel Vogel and Ravin Balakrishnan. 2004. Interactive public ambient displays: transitioning from implicit to explicit, public to personal, interaction with multiple users. In *Proceedings of the ACM Symposium on User Interface Software and Technology*, 137-146. http://dx.doi.org/10.1145/1029632.1029656

[115] Stephen Voida, Elizabeth D. Mynatt, and W. Keith Edwards. 2008. Re-framing the desktop interface around the activities of knowledge work. In *Proceedings of the ACM symposium on User Interface Software and Technology*, 211-220. http://dx.doi.org/10.1145/1449715.1449751

[116] Ron Wakkary and Karen Tanenbaum. 2009. A sustainable identity: the creativity of an everyday designer. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 365-374. http://dx.doi.org/10.1145/1518701.1518761

[117] Jennifer Wang and Alice M. Agogino. 2013. Cross-Community Design and Implementation of Engineering Tinkering Activities at a Science Center. In *Proceedings of fablearn*, 1-4.

[118] Miaosen Wang, Sebastian Boring, and Saul Greenberg. 2012. Proxemic Peddler: A Public Advertising Display that Captures and Preserves the Attention of a Passerby. In *Proceedings of the International Symposium on Pervasive Displays*, 3–9. http://doi.org/10.1145/2307798.2307801

[119] Tricia Wang and Joseph Kaye. 2011. Inventive leisure practices: understanding hacking communities as sites of sharing and innovation. In *Extended Abstracts on Human Factors in Computing Systems*, 263-272. http://dx.doi.org/10.1145/1979742.1979615

[120] Jiajie Zhang. 1997. The Nature of External Representations in Problem Solving. *Cognitive Science,* 21(2):179-217. http://dx.doi.org/10.1207/s15516709cog2102_3