3D PRINTING, MAKERSPACES AND INNOVATION: A BRICOLAGE PERSPECTIVE

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ABSTRACT

The aim of this research is to understand how 3D printing is used by independent innovators, in the context of makerspaces, to generate innovations. 3D printing refers to digital fabrication technologies that are increasingly affordable and accessible. Makerspaces allow communities of individuals to share access to such technologies, learn to use them and to develop their social capital. The objectives of the research are 1) to understand the motivations of innovators who use 3D printing and makerspaces; and 2) to explain the role that 3D printing and makerspaces can play in commercial innovation. The study presents case research involving individual innovators who were identified through ethnographic fieldwork in a number of makerspaces. The research draws on theory in the area of bricolage – an approach to innovation that emphasises experimentation, improvisation and networking to overcome resource-constraints. We find evidence that makerspace users adopt such an approach, for example accessing technologies and knowledge. And we demonstrate how 3D printing is used to produce non-standard parts that are combined with available components, when required resources are out of reach. This research contributes to knowledge and practice, by showing that 3D printing is used to fill gaps, by creating non-standard or otherwise unobtainable parts, in combination with other available resources. Makerspaces help innovators to overcome their resource constraints, but also play a crucial role in sharing knowledge, to help individuals innovate. The implications for practice centre on the innovative potential for product innovation to follow the approaches that are now standard in software development – the research therefore illuminates the changing role of innovation in the digital age.

Keywords: 3D printing, makerspace, bricolage, open innovation, open-source innovation

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INTRODUCTION

Innovation is increasingly reliant on digital fabrication technologies, most notably Three Dimensional Printing (3DP). This is a set of processes for turning digital designs into physical artefacts, quickly and cheaply – i.e. without requiring specialised tooling or high volumes. Adoption of 3DP technologies has rapidly increased (e.g. D'Aveni, 2015) in recent times and research increasingly highlights the opportunities 3DP offers for transforming data into innovative products (Rindfleisch et al., 2017; Candi and Beltagui, 2019). Central to the recent growth of 3DP is the involvement of *makers* (Anderson, 2012) and *makerspaces* (Halbinger, 2018). The former are individuals who seek to design and create products, for commercial reasons, but often also due to curiosity, a desire to learn or simply as an opportunity to socialise with like-minded individuals. The latter describe communities and the spaces where they meet to access shared resources including 3D printers, to learn about design and technology or to meet other makers.

We define makers as individuals who innovate independently, to create or contribute to creation of physical artefacts, without the resources or directions of commercial organisations. Makers engage in open design of physical artefacts (Raasch et al., 2009, Van Abel et al., 2011), behaving in similar ways to open-source software developers by contributing their efforts even where there is no direct monetary recompense (von Hippel and von Krogh, 2003; Lakhani and von Hippel, 2003). An example of open design is the RepRap project (Raasch et al., 2009), which sought to create an affordable, open-source 3D printer, which would be self-replicating, i.e. capable of producing the components used to produce it. This project created the blueprints for most of printers used by makers around the world, including commercial ventures such as Makerbot Industries (West and Kuk, 2016).

Makerspaces have also grown, as the opportunities of digital fabrication attract makers, with the promise of making almost anything (Gershenfeld, 2012). Makers may seek to turn their ideas into commercially viable products (Anderson, 2012), but many see makerspaces as an opportunity to democratise innovation by giving wider access to means of producing goods (Rigi, 2013). Following Halbinger (2018), we define makerspaces as places in which groups of individuals gain access to shared fabrication tools (such as 3D printers), share information, collaborate on projects or socialise with others. Makerspaces are often community run and not for profit, but also include subscription services such as the global network of Fabrication Laboratories (FabLabs), creating a social movement (Walter-Hermann, 2013). While there is some evidence that this movement enables open-source innovation and commercial outcomes (Mortara and Parisot, 2016), there is little understanding of how makerspace participants innovate. While open-source innovation research explains motivations of innovators and what leads to commercial success (e.g. Mendonca and Sutton, 2008) how this relates to open design and digital fabrication of physical goods is unclear.

Gaps in knowledge remain in terms of how individuals interact with makerspaces and makers, their motivations for joining such communities and what role technologies such as 3DP play in their innovative and entrepreneurial ventures. The purpose of this study is to address these gaps in knowledge by understanding how and why individuals use 3DP, within makerspaces, to develop and commercialise products. We contribute to knowledge by examining case studies, drawn from an investigation of multiple makerspaces in the UK. We focus on individuals who have attempted to innovate and provide snapshots at various points of the innovation process these individuals follow. To interpret their narratives, we apply the lens of bricolage (Cunha, 2005; Wittel et al., 2017). The concept of bricolage has been used in innovation research to explain how innovators utilise available resources in creative ways, to solve unpredictable problems (e.g. Baker et al., 2003; Senyard et al., 2014).

Whereas 3DP is often discussed as a means to create entire products, our research highlights its value in producing components that can be combined with standard parts in unexpected ways. And makerspaces play a vital role in giving individuals access to tools such as 3DP, but perhaps more importantly, a means of sharing and gaining knowledge or ideas. Our contribution to knowledge is to demonstrate the value of 3DP and makerspaces as enablers of innovation through bricolage.

BACKGROUND

Phenomena such as open innovation and customer co-creation have shifted the focus of innovation management outside of established firms. In parallel, widespread digital connectivity has enhanced the information and resources available to individuals, and hence their ability to innovate and co-create. 3DP in particular offers individuals enormous opportunities to transform their ideas into innovative products, through their own efforts and through open design in physical and virtual communities (Raasch et al., 2009; Rayna et al., 2015).

Some firms have begun to use 3DP as a means to create customised products for their consumers, for example Adidas' Futurecraft range of apparel that can be 3D printed in store or Nu headphones, made to measure while the shopper waits. The focus of this research, however, is on how individuals themselves use 3DP and makerspaces to enable innovation and entrepreneurship, without reliance on companies. We review literature on 3DP and makerspaces, to establish current understanding in relation to innovation management, then consider how bricolage may support advancing this understanding.

3D Printing

3DP refers to a range of digital fabrication technologies, which create products by building up layers of plastic, metal or other material, directly from a digital design file (Rindfleisch et al., 2017). Since the first of these processes was patented in 1986, the range of technologies has grown and matured. And applications for 3DP have gone from prototyping early in the innovation process towards creation of end-use parts downstream (D'Aveni, 2015; Schniederjans, 2017; Candi and Beltagui, 2019). The social (Woodson et al., 2019), environmental (Despeisse et al., 2017) and economic (Weller et al., 2015) implications are potentially enormous, providing fertile ground for research. Research has examined the impact of 3DP technologies on industrial supply chains (e.g. Khajavi et al., 2014), especially where 3DP allows customers to produce goods at home (Bogers et al., 2016). 3DP facilitates distributed manufacturing, since resources can be shared through digital transfer of designs for production closer to their point of use (D'Aveni, 2015). Additionally, it not subject to the economies of scale that hold for traditional manufacturing since there is no cost penalty associated with low volume production. As a result, on demand production of customized products to suit the needs of individual customers becomes economically viable (Weller et al., 2015).

3DP is an enabler of open innovation, defined as "free revealing of information on a new design with the intention of collaborative development of a single design or a limited number of related designs for market or nonmarket exploitation" (Raasch et al., 2009, p.383). Indeed, the development of desktop 3D printers, which are now affordable to most consumers, itself draws on open design through the RepRap project. Anderson (2012) suggests that humans are inherently predisposed to making, which some express through activities such as gardening or cooking, but that the increasingly digital nature of life and work limits exposure to physical making. Part of the appeal of 3DP, therefore, is that it allows would-be makers to move from digital design to physical production, to make and repair rather than passively consume. Studies of makers have focused on physical communities such as Fablabs (Walter-Hermann, 2013) or makerspaces (Halbinger, 2018) as well as online communities that practice open design in a similar manner to open source software communities. The appeal of such communities lies not in financial gain, but in the opportunities for skills development and social interaction (Nambisan and Baron, 2009). Open design, enabled by 3DP,therefore represents an important source of innovation for manufacturers that are able to engage such communities (Van Abel et al., 2011), while maintaining the spirit of openness that drives them (West and Kuk, 2016).

Makerspaces

Makerspaces are digital fabrication workshops, providing open access to tools including 3D printers, that are maintained for collective and funded by subscriptions or donations (Hielscher and Smith, 2014; Halbinger, 2018). These spaces vary in format and are known by alternative names such as Makerlabs, Hackerspaces or Fablabs. Research on makerspaces is thus far quite limited. Svensson and Hartmann (2018) demonstrated that professional makerspaces can support user innovation. Their study examined the innovative outcomes of clinicians using a makerspace run by a Swedish hospital, identifying a tenfold return on investment in the first year of operation. Professional makerspaces have been instigated by a variety of organisations, including BMW, to capture the benefits of employees' creativity by allowing them to experiment with and prototype their ideas. Halbinger (2018) expanded the scope of research by studying non-professional makerspaces, in which individuals are innovating or tinkering at their own discretion. A comparison with data from national innovation surveys suggests that makerspaces are associated with a substantially higher innovation rate and that the rate of diffusion of the innovations is also higher than usual.

Halbinger's study deliberately avoided using the term *innovation*, acknowledging that associations with commercial activity to generate revenue from creativity, is viewed with suspicion by some makerspace users, who prefer the term *hackers*. One characteristic of makerspaces is that they give individuals the means to produce almost anything, which holds political and ideological appeal for some users (Rigi, 2013; Gershenfeld, 2012). The openness encourages altruistic collaboration and exchange of ideas, while overtly commercial motives, particularly where they restrict freedoms, have been known to be poorly received by maker communities (West and Kuk, 2016). Viewing makerspaces from the perspective of entrepreneurs, Mortara and Parisot (2016) produce a classification that considers factors such as cost and equipment quality, to identify suitability for ideation, development or (low-volume) production. Makerspaces are considered by many to be a vehicle for entrepreneurship (Anderson, 2012; De Jong and De Bruijn, 2013). And in this respect, emerging theoretical models of digital entrepreneurship (Nambisan, 2017) may be helpful, but empirical evidence is limited. One study of entrepreneurs (Mortara and Parisot, 2018) documents the interaction with makerspaces, and how availability of resources contributes to innovation. However, there remain gaps in knowledge, in relation to the motivations of makerspace users and, particularly, the factors that may lead to success and failure when commercialising innovations.

Bricolage

The term bricolage was first used by Claude Levi-Strauss, to explain a particular form of sense-making in societies. He contrasted the *bricoleur*, someone who will achieve results with whatever is at hand, with the *ingénieur*, who is guided by rationality and scientific principles (Duymedjian and Rüling, 2010). Whereas planning seeks to fit problems into a pre-existing structure, bricolage is more likely to involve starting with a problem and seeking a structure to solve it (Cunha, 2005). In this sense, the bricoleur follows what may now be referred to as design thinking, by following an abductive reasoning approach, experimenting, developing prototypes and testing ideas, rather than building detailed plans in advance.

Innovation research has used bricolage as a lens to investigate how resource-constrained, often new firms, derive benefits from bricolage. Baker et al., (2003) focus on improvisation, in which the design and implementation of novel solutions converge. They propose that building improvisational capabilities, including through drawing on networks, helps in overcoming resource-constraints. Similarly, Senyard et al., (2014) identified that new firms benefit from the ability to recombine available resources in unintended or unexpected ways. This contributes to an ability to innovate through design, regardless of their ability to invest heavily in R&D (Moultrie et al., 2009). Indeed, in service innovation, which rarely relies on R&D and may even be unsuited to planned processes, bricolage is proposed as a useful approach (Witell et al., 2017). Similarly, scholars of entrepreneurship have focused on the experimentation used by entrepreneurs who cannot easily build or access resources (Kerr et al 2004; Vanevenhoven et al., 2011). Management researchers are familiar with the resource-based view that emphasises development of capabilities and allocation of resources. These activities may be inappropriate when innovating in unfamiliar contexts, with problems that are not well defined or not suited to existing resources (Beltagui, 2018). In such contexts, bricolage succeeds by emphasising experimentation and improvisation to generate unexpected responses to unanticipated problems (Cunha, 2005). For example, when forced to change plans during the Apollo 13 mission, astronauts and their colleagues on Earth relied on bricolage to fashion solutions from such resources as duct tape, clothing, unused pages of instruction manuals (Rerup, 2001).

Theoretical framework

To identify and examine the influence of bricolage, we adopt the theoretical framework that emerges from Witell et al.'s (2017) review of literature. They outline four crucial and interconnected components of bricolage. First, addressing resource constraints actively, which is required by resource-constrained new firms, but also by individuals who seek to innovate independently. While digital technologies in the form of the personal computer and the world-wide-web have enabled software innovation, we investigate whether and how 3DP and makerspaces can do likewise. Second, making do with what is available, which is a crucial difference between bricolage and other innovation mechanisms. 3DP is considered by many to be a means of making everything, but the outputs of desktop 3D printers are often not of comparable quality to mass produced goods, so an element of compromise may be expected. Third, improvising when recombining resources, in which innovation emerges from creative combinations rather than new developments. Makerspaces offer an opportunity to share ideas and resources, while we also investigate how 3DP may be combined with other approaches in creative ways. And finally, networking with external partners, a crucial way of accessing resources for new firms or for independent innovators. Makerspaces offer a route to build social networks and we investigate how this may support innovation through bricolage.

METHODS

An ethnographic approach was used in order to understand the motivations and methods of 3DP users and makerspace participants. This approach has been used to study design teams and their methods in organisations (Sutton and Hargadon, 1996; Hargadon and Sutton, 1997), and more widely for understanding interactions and sensemaking within groups of people (Chambers, 2003). We adopted an approach in which the research design and theoretical explanations evolved in parallel with the data collection (Dubois and Gadde, 2002). Users of 3DP were identified through observation of individuals in makerspaces. These individuals were invited to semi-structured interviews that explored their background, motivation for 3DP use in the makerspace and objectives they sought to achieve. Interviews were recorded, transcribed and summarised for reporting to participants. Weekly review meetings were conducted in which analysis was conducted and next steps were agreed e.g. the topics emerging from previous interviews were identified and the next interviewees to target. To support reliability of the analysis, two of the authors, who did not participate in fieldwork were able to act as outsiders (Evered and Louis, 1981), reviewing the results from a critical perspective. Additionally, the authenticity, plausibility and criticality of the narratives were emphasized in order to convince readers (Golden-Biddle and Locke, 1993).

Fieldwork was conducted in makerspaces located in the UK, by an experienced researcher with prior expertise in 3DP and past experience of setting up a makerspace. Data collection was carried out over a six-month period, involving participant observation. The researcher visited each makerspace on a weekly basis, working on his own projects and building a rapport with makerspace participants, including using his expertise to offer advice and assistance. Field notes were used to capture observations and reflections, while face-to-face interviews, lasting an average of 2 hours, were conducted with individuals only after observation and informal conversations.

In line with the ethnographic, fieldwork approach, we started with a general research question, namely what motivates makerspace users to use 3DP? This follows Sutton and Hargadon (1996), whose initial research question was "how does IDEO innovate routinely?" (p4). The theme of bricolage emerged through analysis of the initial interviews and observations, since we saw individuals attempting to start businesses or develop products using 3DP where they lacked the monetary, social or technological resources that would normally be expected for innovation.

Makerspaces take a variety of different forms (Mortara and Parisot, 2016; Halbinger, 2018). To examine a range of motivations, the fieldwork involved different makerspaces along a continuum from exploratory in nature (i.e. open to users with no specific innovation objective) to those focused on delivering specified innovation outputs. We present a number of case studies of makerspace users, analysed using the lens of bricolage. Table 1 presents the selected cases (selected from among the interviewed makerspace participants due to a perceived commercial motivation) and states the makerspace that each informant participated in. Makerspace C is a newly established community in a suburban area, which largely attracted older users keen to experiment with new ways of working or to learn about new technologies. Makerspace A is a more business-oriented makerspace, providing funding for startups or social enterprises and was therefore more akin to an incubator, albeit with an emphasis on makers. As with any qualitative research, depth of investigation comes at the expense of breadth, so the cases presented cannot claim to be comprehensive, but the aim of the case selection is to explore and identify categories, to identify common themes.

Table 1 – Details of cases - 3DP users identified through ethnographic study of makerspace participants

3DP User	A1	A2	B1	C1	C2
Makerspace	A. Subscription based makerspace/incubator, supporting startups and social enterprises. Attracts mainly young graduates and entrepreneurs, particularly those with art and design related education.		B. Subscription based makerspace, mainly used by professionals developing hardware Also member of makerspace C.	C. Free makerspace, run by local residents and attracting a variety of members, mainly middle-aged males with an interest or background in science and engineering.	
Background experience (Age)	Design Engineer (30s)	Designer Engineer (20s)	Scientist and Engineer (40s)	Software Developer (20s)	Electromechanical Engineer (70s)
Motivation for makerspace participation	Member of company developing/producing micro-climate monitoring hardware, including 3DP components, for agricultural use.	Developing products with potential for commercialisation, including wire forming device made with 3DP components.	Working on several projects with potential commercial applications.	Developing products and developing knowledge for possible future commercial applications.	Developing products and developing knowledge for possible future commercial applications.
3DP and design experience	Engineering design graduate, with experience of 3DP and CAD through education	Professional product designer and artist, with experience of 3DP for personal and professional projects.	Experienced CAD and 3DP user with experience in product prototyping as well as development of makerspaces.	Experienced maker, used 3DP technologies in several personal projects.	Early adopter of 3DP, used in several personal projects.

RESULTS

Makerspace users vary broadly in their personal characteristics, motivations, objectives and the tools that they use. They share, however, an interest in creating artefacts for personal or commercial use, and a desire to create or gain skills. We focus on makerspace users whose desire to create has some commercial objective, either the immediate goal of setting up a business and selling products (e.g. A1, B1) or a more long-term objective of developing viable products or exploring future career options (e.g. A2, C2). Makers use various tools, including laser cutters, sewing machines and other digital and physical tools. We focused on makerspace users who have some commercial innovation objection and who make use of 3DP. Through initial observation of these users, bricolage emerges as a useful lens to understand how 3DP and makerspaces can contribute to innovation. Table 2 summarises the cases and their analysis, following Witell et al.'s (2017) bricolage framework.

Table 2 - Summary of cases, revealing the role of 3DP and makerspaces in innovation through bricolage

	A1	A2	B1	C1	C2
Addressing resource scarcity actively	Member of a startup that was launched while founders were students, who made use of subsidised access to 3DP. Makerspace membership helps maintain 3DP access despite limited investment in new business.	Focus on social projects, e.g. developing low-cost air quality measurement device, has helped secure funding to access makerspace resources.	Has been an active participant and proponent of open-source communities, so uses makerspaces as a means of furthering open-source and resource sharing, particularly for individuals who lack their own innovation resources.	Relies on makerspace for otherwise unavailable access to 3DP and support for learning.	While he has access to 3DP at home, makes use of makerspace to access machines and share his knowledge with others.
Making do with what is available	Make use of leftover materials found in makerspaces, including offcuts of wood, plastic, metal or cardboard. Uses 3DP to produce missing parts that cannot be cheaply acquired, or to create temporary alternatives to parts for machining in future. Continuing to produce products for customers using 3DP, but now working towards higher volume production solutions.	Adept at using available materials, including cardboard, or balloons when creating prototypes. 3DP has been used to help accelerate ideation and iteration, allowing fast trial and error, but also to enable production of what are often one-off artefacts.	Views makerspaces and associated community as a place to share resources and make devices, e.g. electronics available for all makerspace participants to innovate with.	Uses makerspace as a means of accessing tools and expertise, for example when seeking a way to repair or improve products.	Following a career that included technical development in theatre productions, is adept at using available material to achieve required outcomes. Discusses maker motivation with reference to his grandfather, who helped him learn how devices such as radio work.
Improvising when combining resources	Prototypes combine 3DP parts with available components, for example a plastic food storage container was used as a casing with a tight seal, including for the first demonstrator products produced for field trials. Continuing to use 3DP components combined with standard electronics.	Uses 3DP mechanical components in combination with standard, off-the-shelf parts. In one case, gears were prototyped using 3DP and retained as functional parts.	Uses 3DP in combination with other components, e.g. produced a casing to house electronics when building a moving toy for a child.	Uses 3DP to build housings or custom parts in combination with other materials.	Uses 3DP to make non-standard parts that combine with other materials, e.g. supporting a fellow makerspace participant to make a customised handle for household appliance.
Networking with external partners	Regularly shares knowledge and improvement ideas with other members of makerspace, including 3DP knowledge.	Working largely independently but sharing social network through makerspace.	Helps to establish community in makerspaces, to facilitate networking and information sharing.	Makes use of networking opportunities to gain knowledge and share ideas.	Active in makerspace community, particularly in sharing expertise to help others.

DISCUSSION

Innovation research has long shown a debate between two perspectives on the source of innovations. The idea of the individual entrepreneur, creating new inventions through individual creativity contrasts with the large and well-resourced R&D lab, drawing on the processes and structure of an organisation. Indeed, Schumpeter, who proposed both models, himself disagreed. While studies of success in companies shows that a well-organised process is a crucial success factor (Cooper and Kleinschmidt, 1987). This is particularly the case when products can only be produced by large companies with the development and production resources required. Digital technologies are changing the way that physical goods are created, with implications for the accepted knowledge of innovation management (Nambisan, 2017). While this has been observed over several decades in terms of software development (e.g. von Hippel and von Krogh, 2003), the implications of digital innovation are slowly taking shape in product innovation management (Rindfleisch et al., 2017). The maker movement is proposed as a means of changing the nature of production (Anderson, 2012) and this research examines how it may influence innovation.

We find a bricolage perspective is ideally suited to studying the innovation practices taking shape in the digital age. In particular, the use of digital technologies such as 3DP and interactions through makerspaces do not necessarily entail a revolution, but an evolution. Rather than replacing traditional innovation by overthrowing companies (Rigi, 2013), 3DP and makerspaces offer a means of supporting and broadening innovation by enabling co-creation (Witell et al., 2017). In this sense, digital technologies support the aim of democratizing innovation by allowing more people to turn their ideas into physical goods and to actively participate in collective design projects (Raasch et al., 2009; van Abel et al., 2010). What holds individuals back is typically a lack of resources. This refers to a range of prerequisites for innovation, but as table 2 demonstrates, key among these are knowledge, technology and access to markets. 3DP helps to fill resource gaps when used within a bricolage approach, to replace components or materials that are not readily available. We see the focus being on components, rather than products, in other words the combination and repurposing that are characteristic of bricolage come into play. And makerspaces help to give access to resources, including technology but also relating to social connections and knowledge that can support innovators in achieving their aims.

Innovation through bricolage

Our results are analysed using bricolage as a theoretical perspective. Table 2 shows some highlights, which are discussed here.

<u>Addressing resource scarcity actively</u>

In all of these cases, the individuals innovate independently, using their own funds and devoting their time to further their ambitions. As a result, all of them face resource scarcity in terms of money, equipment and knowledge. They address this scarcity through makerspaces. In this context, access to technology is free or at least more affordable. And this is made possible by the ease with which digital technologies can be shared – e.g. 3D printers are shared in the same way that computers are available for shared use in libraries, schools and universities. In addition to equipment that can be accessed, makerspaces allow sharing of knowledge. We see individuals volunteering their time, or seeking support from others, in order to learn about technologies or to gain assistance in overcoming technical challenges. An example was informant C2, who required help in designing and printing casings for electronic components, or C1, whose career experiences give a basis for helping other makerspace users.

One of the key advantages of 3DP is the ability to share capacity (De Jong and De Bruijn, 2013; D'Aveni, 2015). This is both a result of increasing reliability and maturity of technology but also because of the digital nature that makes it easier to operate equipment and send design files to it. Makerspaces of different types help participants to overcome resources constraints in different stages of their innovation processes, for example ideation, development and production (Mortara and Parisot, 2016). In doing so, the challenge of accessing financial resources is potentially reduced for innovators, since they are able to develop, prototype and test concepts before seeking funding. The approach they take may also be more appealing to investors who value the bricolage approach in reducing risks involved (Kerr et al., 2004). Predictions of a 3D printer in every home seem increasingly less realistic, and the growing use of makerspaces, with their shared access to such devices may help to explain why – those who need access to 3DP can do so even if they cannot afford their own printer.

Making do with what is available

Makerspaces give access to people and equipment, as a result they also provide a wealth of materials that can be re-used. We see makerspace participants making use of available materials such as off-cuts from projects carried out by others. These are not the perfect materials, or what would be planned in advance, but are suitable for bricoleurs who are willing to make do. Similarly, 3DP is not the answer to all problems and is certainly not a perfect replacement for all production methods. It is, however, very valuable for quickly and iteratively producing components that are good enough. For example, several users create housings or casings for devices, because they lack the financial resources to invest in tooling for mass produced (and much higher quality) parts. This is likely to be a stop-gap, as shown by A1, whose company is now looking to scale up by gaining investment, but only after using 3D printed and "hacked" solutions to build initial products.

As Halbinger (2018) demonstrates, making do with satisfactory but creative, rather than perfect solutions is central to the identity of makerspace users. These individuals often prefer to be seen as hackers than innovators, although from an analytical perspective, we identify them as engaging in innovation. Hargadon and Sutton (2000) used the term *innovation brokers* to describe a similar approach, in which innovators use whatever materials are available, they refer to Thomas Edison to argue that innovation demands "a pile of junk" (p160) that can be accessed. Makerspaces allow almost anyone to access such junk and find new ways of using it to create innovations.

Improvising when combining resources

Closely related to making do, is improvisation and resource re-combination. A striking example was described by A1, who discussed an early demonstrator, created by collecting and assembling parts that were repurposed, but combined with 3D printed components. When faced with the challenge of creating a working demonstrator that could operate in the field for around 6 months, it was acceptable to use parts that would be good enough to survive that long, but would not be permanently in place. Crucially, the use of 3DP in this process is to support bricolage:

"We used PVC piping that wasn't meant for that purpose at all, we just repurposed it because it was available, it was cheap…we used a plastic lunchbox to house the electronics, the main parts that were 3D printed were the interfaces – so how to get the

lunchbox onto the PVC piping…specific custom designs were 3D printed, but around 90% of the product was hacked together from standard parts." (A1)

The literature discusses the role of 3DP in various stages of innovation (Candi and Beltagui, 2018) and also how 3DP provides an alternative to traditional production approaches. Yet the complementarities are not so clearly outlined in prior literature. What we see from examples such as this is the way that the bricoleur's approach to combining whatever is available has its limits and the value of 3DP is to overcome such limits. For example, while repurposed parts can achieve certain functions, they may be difficult to connect in a suitable way. Or in other examples, electronics may require a customised housing that cannot easily be created. 3DP components in these products may only be a small proportion of the whole thing, but can be very important parts, without which the innovation may be impossible.

<u>Networking with external partners</u>

We refer to examples from three makerspaces that were investigated, each of which has a different character but all three encourage and promote openness. In makerspace A, with a clearer focus on commercialising the innovative activity of participants, the use of hot-desks and break-out areas supports interaction between the individuals and companies. Networking is possible and actively encouraged, helping people to collaborate and develop their innovations and generate solutions to technical problems or overcome constraints through social capital. Within the space, openness is encouraged although there is a filter – participants must pay for access or are given some months of access upon meeting criteria as a social enterprise. Similarly in makerspace B, subscription ensures commitment, but a spirit of openness is deliberately encouraged. Finally, in makerspace C, openness extends to free access, encouraging many first time makers to attend through curiosity. While we observed limited interactions, perhaps due to individuals focusing on their own projects, we saw users developing their social connections over a period of time. And individuals expressed their desire to support others as well as seeking to learn from other makerspace participants, enabled by openness. For example, while discussing open-source software:

"the collective assistance you can get from the community is something that I appreciate, where you can trace the original developer and inform them about important updates. For me all of these are very positive, meaning the importance of free culture. One of the frustrations I had is when you try and get in touch with proprietary software developers and what you get is a non-cooperative response and also you are not allowed to modify their work. I understand that this is their intellectual property but I am keen in working where IP is shared and not restricted" (B1)

The parallels are clear because this person looks for the same openness in makerspaces as he has experienced in software innovation. The importance of networks, and the ability to create them is clear from how he views the community.

Theoretical contributions

The first contribution relates to the potential contributions of 3DP in innovation. Using the bricolage perspective we see that 3DP helps to fill gaps. This includes overcoming resource constraints by giving access to the capability to prototype, develop and produce parts. Our results highlight that this is often not entire products, but rather specific components in support of a bricolage approach. We observed several individuals who visited makerspace C, but did not return, because they may not have had the required mindset or demonstrated sufficient commitment to innovate. This mindset appears to be developed early in life. Individuals talked of their background, recalling how parents or grandparents had encouraged them to learn through creativity and making. For example,

"we weren't watching a lot of TV, there was not so much of the passive entertainment, we were encouraged to play outside, kind of build our own worlds and that didn't dictate any world, you could do whatever you want to…back in the day I didn't think much of it, but now I think it probably was a main drive for me to choose that direction… I have changed and lego has changed, it has gotten a lot more directed, I feel like it does steer kids in a direction of what to play…it has become a bit more limiting" (A1)

"Ever since I was young I used to enjoy just messing about with things that worked. I think my inspiration was my grandfather, who loved to listen to an old radio …I thought that it was magic that these voices were coming over the air and that you could tune into them….I was enthusiastic about radio and how the magic of it works…that same grandfather showed me how to use workshop tools." (C2)

In these examples, it is clear that the individuals have a desire to make something, which they associate to their education and childhood. In an increasingly digital world, in which purchases are made electronically, without viewing physical goods, the sensory aspects of making, enabled by 3DP, are appealing. Interestingly, Anderson (2012) opens his account of the maker movement by describing his own childhood memories of being taught to use workshop tools, before digital technologies broke this connection to physical making. The appeal of 3DP is partly due to the familiar digital tools (such as CAD) being used to generate products in previously unimaginable ways – unimaginable because of resource constraints that can now be overcome.

The second contribution relates to the social interactions inherent in makerspaces, and how these physical and virtual communities support innovation through bricolage. Informants discussed how they benefit from the knowledge of others and the shared resources they can access, but also their own motivation to support others:

"I do some volunteering work for a charity who help people with disabilities solve practical problems using engineering. In this case 3DP comes in very handy since you can make one of a kind customised parts very quickly." (B1)

Managerial implications

In recent years, managers have been bombarded with unrealistic predictions that 3DP will disrupt or revolution the industries they work in and change the world in previously unforeseen ways. As these predictions give way to more realistic analysis, this study can help shed light on the ways 3DP complements (not replaces) other methods, to support innovation. Meanwhile, the benefits of makerspaces for innovation management have not been extensively explored, particularly since these are typically regarded as spaces for independent and undirected exploration, rather than commercial innovation. Our research demonstrates the similarities and differences between makerspaces, for example those focused on supporting communities and those aimed to accelerate innovation by startups. The identities of the participants vary, for example between those who see themselves as makers and hackers. And these distinctions also hint at political or ideological differences.

For managers, makerspaces and 3DP can be relevant as means to develop innovations. While some of the individuals interviewed were relatively early in their exploration of ideas and others had not achieved any successes, we saw A1 in particular as part of a growing company, delivering products and securing contracts with relatively large customers. Their success to date lays the foundations for further refinements and developments to their products, to enable higher volumes and improved quality. The roles of 3DP and the makerspace they work in are crucial to them reaching this point. Without 3DP, they would have considerable difficulties in building products, without which they may have struggled much more to attract initial investment. And without the access to resources that makerspaces afford, using 3DP may have been more challenging. We observe the bricolage approach to be crucial in their ability to use the resources they access, suggesting that the right people or the right way of working is needed to make the most of makerspaces and 3DP.

Additionally, this research raises the prospect of 3DP and makerspaces being used to develop the approach and mindset of the bricoleur. Faced with rapidly changing, uncertain environments, managers should nurture bricolage within their organisations. This research demonstrates how bricolage appears to be a character trait among makerspace participants and 3DP users. Whether bricoleurs join makerspaces or makerspace participants become bricoleurs, however, may require further research. In the meantime, managers may consider using makerspaces to engage their employees and develop valuable skills for innovation. While this idea has been widely recognised in schools, colleges and universities, perhaps the next step should be to test makerspaces as a means of continuing development among adults, to help keep pace with changing technology.

CONCLUSION

Literature on 3DP implicitly or explicitly reflects on the implications of replacing traditional production methods or allowing consumers to become producers of goods. While some makers do see 3DP and makerspaces as a means of breaking free of dependence on companies, this research suggests that they are complements. Just as open-source communities have supported, or perhaps even increased the dominance of, companies, makerspaces and 3DP have the potential to allow open design communities to do the same.

3DP allows a freedom of expression since it enables the creation of almost any products by willing makers. Our first contribution is to demonstrate how this facilitates innovation, not by replacing all other production methods, but through combination with more traditional methods. In particular we find innovators use 3DP where specialised components are required, and off-the-shelf components are insufficient. 3DP supports bricolage by allowing makers to fill gaps, helping them to make do with available resources and create new products. Our second contribution is to demonstrate how bricolage is enabled by using 3DP within the context of makerspaces. Innovation through bricolage normally involves innovators compensating for resource constraints through networking, and makerspaces facilitate this through access to people and knowledge, as well as potentially unaffordable technology. Our third contribution is to highlight the differences in motivation and in mindset between makers, suggesting the need for further research to investigate how far makers can go as innovators. While the maker movement has been named and discussed for several years, it has not yet led to a clearly identifiable trailblazers such as Mozilla or Google in open-source software innovation. Future research may uncover the paths taken by such trailblazers in open design and those who follow them in the coming years.

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