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A bricolage perspective on democratising innovation: the case of 3D printing in Makerspaces

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ABSTRACT

The availability of digital technologies such as 3D printing can allow members of the public rather than only producers, to innovate. Makerspaces, where communities of individuals share access to such technologies may therefore support the democratisation of innovation. Yet little is known about how and why makerspace members use 3D printing to realise their creative and commercial ambitions. Through an ethnographic study, we identify a bricolage approach whereby makerspace members combine 3D printing with whatever resources are at hand in a makerspace, to generate innovations that otherwise may not be realised. In this context, we find bricolage entails synergy - combining resources in creative ways - and openness - a willingness to gather and share resources. We confirm that bricolage restricts commercial growth such that a need for more structured processes and perhaps a move away from makerspaces eventually becomes necessary. We contribute to theory by presenting makerspaces as a route to innovation in resource constrained contexts, or those in which neither a problem nor solution are clearly defined. This contrasts with crowdsourcing where problems but not solutions are defined, and R&D where both problem and expected solution are defined.

Keywords: Bricolage; 3D printing; Makerspace; Democratising; Crowdsourcing; Do-it-yourself

1. Introduction

Estimates suggest there are over 16 million home innovators in the US who contribute over $40m of research and development (R&D) to the economy but gain Intellectual Property (IP) protection for less than 9% of their innovations (Sichel and von Hippel, 2019). Since von Hippel coined the term democratising innovation (von Hippel, 2005), it is increasingly accepted that many, if not most, innovations originate from the ideas and efforts of users. Companies are better placed to refine and commercialise innovations. Meanwhile, independent innovators often achieve little return on their efforts when work independently and do not apply a business logic but devise products, processes and technologies through curiosity, exploration, and experimentation (Von Stamm, 2008). Their innovation may be democratic, but it is often inefficient, expensive, and unsuccessful. So why do they engage in do-it-yourself innovation when the rewards are limited, and buying things is easier and often cheaper than making? Few studies (e.g. Rank et al., 2004; Wu et al., 2014) have explained individuals' inclination to independently conduct innovative projects of their own inspiration and invest the necessary resources to reach tangible outputs. Researchers focus on innovations created by companies and entrepreneurs or co-created with consumers. Less is known about why do-it-yourself innovation funded by individuals or philanthropists (Sarpong et al., 2020) takes place, as well as how technological or social means could improve its success.

The traditional conception of innovation is a linear process of scientific discovery, followed by R&D that focuses on creating products for commercialisation (Hindle and Yencken 2004; Schot and Steinmueller, 2018). In this conception a problem is typically defined in advance, for example how to turn a scientific principle into a saleable product, and the purpose of R&D is to realise the envisioned solution. Due to the large investments involved, only in-house experts are trusted but the wisdom of excluding external parties, such as potential users, has been repeatedly questioned (e.g. Kline and Rosenberg, 1986; Rothwell, 1992; Chesbrough, 2003). Instead, benefiting from external contributions can increase the likely success of innovation

(Gassmann, 2006). In this vein, crowdsourcing has offered ways of facilitating innovation from external sources (Seltzer and Mahmoudi, 2013) to finance the relevant solution-sourcing activities at a relatively low overall spending (Davis et al., 2015).

Crowdsourcing involves outsourcing an activity, such as R&D, to an undefined and large group of individuals through an open call (Howe, 2006). For example, Innocentive, an online crowdsourcing platform, allows firms to present R&D challenges to a crowd of solvers who are remunerated for achieving a satisfactory solution. It relies on the wisdom of crowds (Surowiecki, 2005) – the assumption that a diverse and independent collection of individuals is likely to make better decisions than experts (Adamides and Karacapilidis, 2020). Unlike outsourcing or in-house R&D there is little control over who will answer the call and what they will produce (Poetz and Schreier, 2012). The nature of the problem must therefore be carefully specified, to ensure that the solution meets expectations (Brabham, 2008). Where the challenge is ill-defined, or there are insufficient resources to review and act on the crowd's suggestions, crowdsourcing may not be effective (Malhotra and Majchrzak, 2014). A potential alternative, which achieves the benefits of external inputs but addresses less clearly defined problems is to rely on the increasing prevalence of do-it-yourself innovation (Aitamurto et al., 2015) and the so-called maker movement (Anderson, 2012).

The maker movement is driven by people who aspire to create their own innovations, not only to act as consumers. They may be hobbyists innovating without commercial motive, entrepreneurs seeking commercial outcomes, or may even be researchers seeking to create knowledge (Langley et al., 2017). Thus, we define makers as members of the general public who innovate independently to create or contribute to the creation of physical artefacts, without the resources or directions of commercial organisations. Makers engage in open design (Raasch et al., 2009; van Abel et al., 2010), behaving in similar ways to open source software developers by contributing their efforts even where there is no direct monetary recompense (Lakhani and von Hippel, 2003; von Hippel and von Krogh, 2003). Meanwhile makerspaces (Halbinger,

2018) are physical locations in which makers share information, collaborate on projects, socialise with other makers, and gain access to shared fabrication tools such as 3D printing (3DP). Makerspaces are often community run and not for profit. They may be free to use or incur a subscription fee as is the case for the global network of fabrication laboratories (fablabs). They have helped create a social movement (Walter-Herrmann, 2013) that enables do-it-yourself innovation and helped democratise innovation by giving wider access to tools for producing goods (Davies, 2018; Rigi, 2013). From an empirical research perspective, there is some evidence that makerspaces improve innovation and commercial outcomes (Halbinger, 2018; Mortara and Parisot, 2016). The members of makerspace communities are citizens, i.e. members of the general public (Franzoni and Sauermann, 2014; Eitzel et al., 2017), who innovate independently. They are neither employees nor necessarily consumers of specific brands, co-creating with companies like Starbucks (Sarpong and Rawal, 2020) or Microsoft (Nambisan and Baron, 2009). Nor are they necessarily entrepreneurs, since some makerspace communities are hostile to commercial motives (Davies, 2018).

Maker communities and makerspaces have gained popularity due to the wider availability of digital fabrication tools, particularly 3DP. While 3DP has been used in rapid prototyping for several decades, it has now become affordable for makers to use in do-it-yourself innovation (Anderson, 2012; Rayna and Striukova, 2016). Gaps in knowledge remain, in terms of how individuals interact with digital fabrication tools, their motivations for joining makerspaces and the role of communities in these spaces.

The purpose of this study is to address these gaps in knowledge by answering the following research question:

RQ: How and why do individuals engage with digital technologies such as 3D Printing, within makerspaces, and how can their do-it-yourself efforts support the wider innovation context?

We examine 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 entrepreneurial bricolage (Baker et al., 2003; Rüling and Duymedjian, 2014; Witell et al., 2017). The idea of bricolage in entrepreneurship and innovation is based on Levi-Strauss' (1966) distinction between ingenieur (the scientific mind) and bricoleur (pensée sauvage, translated to English as savage mind). The latter makes do with whatever resources are on hand (Stinchfield et al., 2013), combining materials in novel ways to 'create something from nothing' (Baker and Nelson, 2005). We explore how makerspace members practice bricolage through their ability to create synergies between physical, information and skills resources along with openness in the accumulation and sharing of such resources. We also find the limits of bricolage, as the constant effort to make do restricts the ability to create efficiency and growth. We therefore contribute to theory by extending the scope of (entrepreneurial) bricolage to do-it-yourself innovation and extending knowledge on 3D printing by showing the role of bricolage in its use. From a theoretical viewpoint, the findings of this research could serve as a starting point for theorizing on the dimensions of do-it-yourself innovation occurring in makerspaces in a more specific manner. Practically, the results will help practitioners understand the role of makerspaces and 3DP, as well as their potential for innovation practice.

2. Literature Review

The source of innovation has increasingly moved from solely within organisations towards a broad range of external sources, particularly users and citizens (von Hippel, 2005; Chesbrough et al., 2010; Franzoni and Sauermann, 2014). Access to digital fabrication tools such as 3DP helps to accelerate this trend in product innovation (Raasch et al., 2009; Bogers et al., 2016; Rayna and Striukova, 2016; Beltagui et al., 2020a). Digital technologies change the way that innovation is performed. For example, Rüling and Duymedjian (2014) examine the techniques used to create visual effects, coining the term digital bricolage to describe the application of digital tools. Similarly, we extend the understanding of entrepreneurial bricolage, by using it as the lens to study how and why makerspace members innovate using 3DP. We first outline the theoretical framework, before presenting the background on 3D printing and makerspaces, which form the context of the study.

2.1 Entrepreneurial Bricolage

Claude Levi-Strauss (1966) used the term bricolage 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). While the ingénieur uses planning to fit problems into a pre-existing structure, the bricoleur is more likely to start with a problem and seek a structure to solve it. In this sense, the bricoleur follows what may now be referred to as design thinking (Brown and Martin, 2015; Dorst, 2011). This is an abductive reasoning approach that involves experimenting, developing prototypes, and testing ideas, rather than building detailed plans in advance of encountering a problem.

Research has used bricolage as a lens to investigate how resource constrained, often new, firms innovate. Baker et al. (2003) focus on improvisation, in which the design and implementation of novel solutions converge. They argue that resource constraints can be overcome by building improvisational capabilities, including through drawing on networks to provide resources. Similarly, Senyard et al. (2014) find that entrepreneurs benefit from the ability to recombine available resources in unintended or unexpected ways. They innovate based on their ability to design novel solutions, rather than by investing in R&D (Moultrie et al., 2009). Indeed, bricolage is seen as central to innovation in contexts that do not rely on R&D and where resources are limited, such as services (Witell et al., 2017).

Management researchers who rely on the resource-based-view may expect managers to focus on building, accessing, and allocating resources. These activities may not be relevant when resources are scarce and when managers are faced with ill-structured problems, unsuited to their existing resources (Beltagui, 2018; Simon, 1973). Instead, they may rely on bricolage in such contexts by improvising and experimenting to generate unexpected responses to unanticipated problems (Kerr et al., 2014; Vanevenhoven et al., 2011). 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, and unused pages of instruction manuals (Rerup, 2015). Stranded in space, the astronauts combined the limited resources at hand in novel ways, while relying on their network on Earth (Baker and Nelson, 2005; Witell et al., 2017). For innovators and entrepreneurs, the challenge may not be quite so extreme. Yet the success of their ventures similarly relies on their ability to make the most of limited resources outside of a well-funded R&D lab. Can digital technologies, such as 3DP, and the availability of these technologies in makerspaces help?

2.2 Makerspaces

The growth of interest in do-it-yourself fabrication and the related maker movement (Anderson, 2012) has helped create a growing network of makerspaces. These are physical workshops that offer shared access to fabrication tools and that are typically funded by memberships, subscriptions, or donations (Halbinger, 2018). We use the term makerspace as a generic term although they are known by other names such as fablabs (Walter-Herrmann, 2013), fab-spaces (Mortara and Parisot, 2016), and hackerspaces (Davies, 2018). Makerspaces serve as access points for human and social capital. They facilitate exchanges of ideas and of physical resources by providing opportunities for interaction between makers. As such, they enable and enhance the outcomes of do-it-yourself innovation. Evidence suggests that makerspaces are associated with higher rates of innovation and with better diffusion of innovations than do-it-yourself innovators normally achieve (Halbinger, 2018). Svensson and Hartmann (2018) find such results in a makerspace run by a Swedish hospital, where they identify a tenfold return on investment in the first year of operation. A number of corporations for example BMW (Hollands, 2015) have begun using makerspaces as an outlet for their employees' creativity, an opportunity to prototype ideas, and a source of innovations. Thus, makerspaces appear to be a promising means of generating open and open source innovations.

Makerspaces, and the tools available in them, give individuals the means to produce almost anything (Gershenfeld, 2012). They are considered a vehicle for entrepreneurship, offering resources at low cost, access to ideas, and opportunities for low- volume production (Mortara and Parisot, 2016). Some makerspace members see these spaces as the driving force of an industrial revolution, enabling wider participation in innovation (Anderson, 2012). These individuals may value openness, as do open source communities (Lakhani and von Hippel, 2003), with expectations that everything is free and open source. For such communities, openness involves the freedom to access, to use and to improve information, but also an expectation that time and resources are shared for mutual benefit.

Indeed, maker communities follow a similar ethos of openness, sharing .stl files (or g-code), just as open source software communities share source code. For community members, the appeal often comes from opportunities for learning, personal development or social interaction, rather than financial gain (Nambisan and Baron, 2009). Manufacturers can generate innovation and financial gain through 3DP-enabled open design (Beltagui et al., 2020a; Cruickshank, 2014; van Abel et al., 2010), and benefit from maker communities' bricolage (Suire, 2019), if they are able to maintain the ethos of openness that underpins them. Conversely, some participants see makerspaces as incompatible with commercial activity, especially where companies exploit makers' work or restrict their freedom to share and use IP (West and Kuk, 2016). They may instead view makerspaces as an opportunity to challenge the market norms of production and consumption (Rigi, 2013). Makerspaces attract a broad range of individuals, some of whom refer to themselves as hackers – a term with connotations of covert or subversive activity – rather than maker or innovator – with its connotations of revenue seeking (Davies, 2018; Halbinger, 2018).

Paradoxically, makerspaces may be open but not to everyone, reflecting "a masculine geek identity anchored by an exclusionary meritocracy" (Hunsiger and Schrock, 2016, p. 537). The communities often lack diversity, being largely populated by white, male, graduates and, whether deliberately or otherwise, may exclude some people (Davies, 2018). Explicitly feminist hackerspaces, makerspaces and associated online communities have been instigated in response (Richterich, 2018). The intersection between innovation, technology and community in makerspaces thus demands ongoing research. To do so, we focus on one technology, which has been particularly influential in the rise of the maker movement.

2.3 Three-dimensional 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 the late 1980s, a range of technologies has grown and matured (Beltagui et al., 2020b). Applications have moved from prototyping in the early phases towards creation of end-use parts for products (Schniederjans, 2017; Candi and Beltagui, 2019). Alongside this progression have come predictions of disruption and revolution (D'Aveni, 2015; Sandström, 2016). 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 (Khajavi et al., 2014), along with home production of 3D printed goods (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 (de Jong and de Bruijn, 2013). Additionally, it reduces the economies of scale that hold for traditional manufacturing, enabling low volume production (Baumers and Holweg, 2019) and facilitating on-demand production of customised products (Weller et al., 2015). 3DP is an enabler of open design (Cruickshank, 2014), 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, 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. In this respect, emerging theoretical models of digital entrepreneurship (Nambisan, 2017) may be helpful, but empirical evidence is limited. There remain some gaps in knowledge, in relation to the motivations of makerspace members and, particularly, the factors that may lead to success and failure when commercialising innovations.

3. Methods

To investigate how and why makerspace members use 3DP to innovate, we adopted an ethnographic approach. Ethnography is valuable to understand social phenomena in context, and gain insights into the experiences of the individuals under investigation. For example, organisational ethnography has been used to study design teams and their methods in organisations (Hargadon and Sutton, 1997; Sutton and Hargadon, 1996), and to understand interactions and sensemaking within groups of people (Chambers, 2003). In the present study, we combine participant observation, through interaction with makerspace members, with recorded interviews, which were transcribed and analysed to support and formalise the observations. We adopted an approach in which the research design and theoretical explanations evolved in parallel with the data collection (Dubois and Gadde, 2002). The selection of cases, the choice of individuals to interview, and the analytical themes were developed simultaneously and resulted in revisiting the literature throughout the study.

3.1 Research setting

Fieldwork was conducted in makerspaces located in the UK, by an experienced researcher with prior expertise in 3DP and rich experience of setting up a makerspace. A number of makerspaces were identified and invited to participate in this project. The aims and expected benefits of the study were communicated, in order to obtain informed consent. Additionally, we made clear that the researcher, as a participant observer, would seek to share his 3DP expertise to help makerspace members with their projects. In the interests of ethical conduct, the researcher's identity was made clear to participants, who were given an opportunity to object to their observation.

Insert Table 1 here

Makerspaces take a variety of forms (Halbinger, 2018; Mortara and Parisot, 2016). 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 (i.e. acting more like business incubators with fabrication tools available). In total, four makerspaces were included and are identified by pseudonyms in Table 1.

MakersLab is located in a suburban area and attracts a number of older members, generally with an engineering or creative background or education, and an interest in expanding their knowledge or learning new hobbies. Although other individuals not fitting this profile would occasionally visit, they often did not return regularly and were therefore not interviewed. For example, one individual visited MakersLab to work on a concept to solve a problem related to transporting equipment in a film studio but did not return so could not be interviewed. Whereas MakersLab members are typically more exploratory in their approach, *MakerStart* provides rented office space and access to a well-maintained makerspace. We interviewed three members of a startup, which has developed a remote monitoring device for agricultural applications and used 3DP to create products, as the search for growth and investment continues. Between these two were *Innov8*, a subscription-based makerspace, providing resources largely used by professionals developing hardware for commercial projects; and *UniLab*, a university-based model shop, available mainly to students, who develop products for academic and potentially entrepreneurial projects. 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.

3.2 Research process

Data collection was carried out over a six-month period, between September 2018 and February 2019. The researcher visited each makerspace on a weekly basis. For example, one makerspace was active on Tuesday evenings, while another was visited weekly every Thursday morning. Ethical approval was granted for the study and a representative of each makerspace was asked to agree participation and inform other makerspace members. As a participant observer, the researcher worked on independent projects while building a rapport with makerspace members, including offering advice and assistance based on their technical expertise. Field notes were used to capture observations and reflections, while face-to-face interviews, lasting an average of 2 hours, were conducted with a total of ten individuals after several weeks of observations and informal conversations with each.

Interviewees were identified according to three criteria, namely they were active participants in one of the makerspaces, were observed using 3DP on multiple occasions, and agreed to be interviewed and recorded. In one case, a makerspace member declined an invitation to be interviewed due to a reluctance to share details of their project. In other cases, individuals were observed using 3DP on one occasion only, or were only seen in the makerspace on one occasion and could not be invited to participate.

Interviews were semi-structured, recorded and transcribed. They explored interviewees' personal backgrounds, motivations for using 3DP, for joining makerspaces, as well as the objectives they sought to achieve. A list of the standard questions is shown in Appendix 1, although the researcher sought to adapt the interview, allowing the participant to expand and explore themes that were not identified in advance but appeared to be of relevance.

Additionally, the researcher's observations of the interview were discussed, to confirm we interpreted the observed actions correctly and to gain greater understanding of the interviewees. The research team conducted weekly meetings in which analysis was begun and next steps were agreed e.g. the topics emerging from previous interviews were identified and the next interviewees to target were agreed. 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, we discussed the results and debated interpretations with the aim of ensuring the authenticity, plausibility and criticality of (Golden-Biddle and Locke, 1993). To ensure fairness and trustworthiness (Guba and Lincoln, 2005) preliminary versions of these narratives were shared with informants so they could comment, add detail and correct any misinterpretations as well as give their approval for their words and images to be used.

In line with the ethnographic, fieldwork approach, we started with a general research question, namely how and why makerspace members innovate using 3DP. We followed Sutton and Hargadon (1996), whose initial research question was "how does IDEO innovate routinely?" (p.4). 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.

3.3 Data and data structure

The research followed four main phases, moving between fieldwork, analysis and literature. Our initial empirical observations suggested the theme of bricolage and led us to develop a coding structure based on prior studies of bricolage (Baker and Nelson, 2005; Witell et al., 2017). We then worked inductively, to derive novel insights through coding based on the empirical evidence (Strauss and Corbin, 1998) in parallel with data collection, before again returning to the literature to consolidate the themes and contextualise the results of the study.

The inductive phase began with open coding, identifying themes that were unexpected or otherwise insightful. Themes were refined through selective coding, reviewing interview transcripts and field notes to identify further examples of the themes and to develop the coding structure. Coding led to a focus on the types of resources shared or combined within makerspaces: physical, information and skills. Additionally, we highlighted a willingness to overlook processes or a requirement to develop processes in order to grow, which helped to demonstrate the limitations of bricolage. Through this process we applied bricolage as a lens, analysed what bricolage entails in this context and the results offer a contribution to the literature on entrepreneurial bricolage.

4. Results

Based on analysis of data, two overarching themes were identified, which we refer to as synergy and openness. The first, synergy, reflects the aspects normally identified in studies of entrepreneurial bricolage, such as the willingness to combine resources in novel ways in order to create value 'from nothing' (Baker and Nelson, 2005). The second, openness, relates to the free revealing of information and intellectual property inherent in open design (Cruickshank, 2014; Raasch et al., 2009; van Abel et al., 2010) as well as the ethos of free and open source software development communities (Lakhani and von Hippel, 2003; von Hippel and von Krogh, 2003). It also reflects the bricoleur's expectation that resources should be shared for collective benefit, and actively accumulated because "they may always come in handy" (Lévi-Strauss, 1966, p.18). The data structure is presented in Figure 1, which is explained and discussed in the following sections.

Insert Figure 1 here

4.1 Synergy

Accepted definitions of bricolage typically emphasise the ability to make do with available resources in order to achieve a result. The bricoleur is a problem solver, who makes use of whatever resources have been accumulated, without seeking out the optimal tools for the job. In this respect, the makerspace provides a resource base, which all of the makerspace members we observed are willing and able to use for solving problems. 3DP plays an important part because it allows the resources to be used more effectively.

4.1.1 Physical Resources

The examples of 3DP we saw were ones in which components, not whole products, were produced. Eric explained how he and his colleagues created a product by using off the shelf components such as solar panels and batteries, machined aluminium parts along with repurposed materials such as a plastic lunchbox as a housing for electronics

> *"…[it] wasn't meant for that purpose at all, we just repurposed it because it was available, it was cheap…the main parts that were 3D printed were the interfaces…specific custom designs were 3D printed, but around 90% of the product was hacked together from standard parts."* (Eric)

The quotation shows how Eric makes do with and repurposes available resources. And it demonstrates how 3DP enables bricolage by helping to turn ordinary parts into something much more valuable. As Eric's colleague explained, the value was in convincing investors who had been intrigued by the concept but unwilling to invest until they could see a functioning product. Using 3DP allowed them to prototype and develop a design to the point of commercial viability.

> *"…back in the day only large companies could afford to drop like 300K on development of a product and not worry about it. Whereas now you can get small startups that can prototype to the stage where you can be pretty confident your design is going to work and it's going to act like you wanted to and then you can move on to*

mass manufacturing." (David)

A similar example came from Ian, who developed the device shown in Figure 2, using 3DP to connect components into something greater than the sum of its parts. As he put it:

> *"Without a 3D printer, this one would be in theory only... but when I do have the prototype in my hand, it turns into a really interesting [product] I have to say."* (Ian)

Insert Figure 2 here

4.1.2 Information

As the examples above illustrate, 3DP facilitates bricolage by enabling (re)combination of physical resources. Makerspaces support bricolage by providing access to these resources, but they also enable synergies that emerge through combinations of information and skills when people interact. For example, Charlie and David had initially been working independently on projects, but recognised an opportunity to combine their work, which led to the start of their company. One was working on software for managing agricultural data, the other was developing hardware for collecting data to assess and triage farming needs.

> *"…we realised that both of those are pretty related. It didn't make sense to do them in isolation. So we brought them together. There was kind of like always that vague commercial element…but we never really, I think, ever had any intentions of making a business out of it… I don't really remember like how the decision was made but we just thought we might as well have a go at it."* (Charlie)

4.1.3 Skills

These examples illustrate two important aspects that can be related to bricolage. Firstly, the willingness and ability of makerspace members to combine information and skills, for example Charlie and David's recognition of synergy between the intellectual property they were developing. Secondly, the willingness of makerspace members to share and combine their skills to achieve valuable outcomes. Similarly, Alan, now retired following a long career, maintains a desire to learn new technologies and to share his experience with others. His career spanned various technical roles, including in theatres as well as contract engineering. He admitted that, despite proficiency in electronics, he struggled with the "mechanical side of things" and sought to learn, as well as sharing his experience with often much younger participants. His desire to fill skills gaps was encountered among several others, for example Harry, who complained that his current, administrative job does not allow for creativity. He sought to update his own skills by learning to use 3DP, with the aim of setting up a business or finding a more fulfilling job.

4.1.4 Processes

In general, makerspace members embraced and benefited from applications of bricolage, using the opportunities to develop their own interests or work on individual projects. While their starting point may be a desire to learn or make, they face barriers when they seek to make money from doing things they enjoy, as Jim identified. Processes that would be standard when developing products commercially, such as safety and quality assurance, are frequently overlooked. The benefits are speed and flexibility, but the risks include a constraint on growth. Charlie and David described their flexibility, including attempts to raise funds by taking on side projects such as developing software for a client. Ultimately, they realised their lack of processes and formal plans made it difficult to do the work profitably:

> *"…if we were a software development firm we'd be charging like 10 times as much… it was a highly stressful period… back and forth with lawyers and stuff and yeah it was really annoying so we're basically like why did you ask us in the first place like? It just seemed like they wanted so much more than was like reasonable like for the price…[eventually they asked us to] write a report [for half of the intended money] scoping what you would do what would be useful they will then use that to develop software in the future…so I think it actually turned out quite well in*

our favour. It probably prevented us from going on with something relatively stupid" (Charlie)

The bricolage approach of adapting one's own skills and resources to solve problems is appealing, but fraught with danger. From this example, it seems clear that the processes required to manage commercial contracts or the knowledge to understand what they entail were lacking. As Charlie, David and Eric have developed their product and company, they seemed to be developing a plan for growth. For example, they have begun planning to scale up production and to recruit staff, both of which demand process development and improvement.

The need for processes was noted when they travelled to visit overseas clients, with the products they had built in the makerspace stored in their luggage. Lacking the resources to ship the products more securely, they made do with the luggage, resulting in predictable damage to some of the products. While making do is necessary in the early stages of a venture, continuing to do so, rather than creating adequate processes could restrict growth in production volume and customer numbers. The limits of bricolage can therefore be seen from this example of a company that may be about to outgrow makerspaces and 3DP.

4.2 Openness

The theme of openness describes both the accumulation and sharing of resources. From the perspective of bricolage, it is important to obtain resources wherever they are available and even when an immediate use for them is not evident. Meanwhile in makerspaces, as in open source communities, there is an expectation of openness in the sense that resources are shared and available to all. Consequently, members are expected to be open to sharing their own resources, time, and effort. We identified this accumulation and sharing in a number of categories of resources, but also saw the limits of bricolage due to the lack of processes guiding the accumulation and maintenance of the resources.

<u>4.2.1 Physical Resources</u>

Bricoleurs typically "scavenge" (Baker and Nelson, 2005) resources that are considered worthless by others. This was most clearly illustrated by George, who described his contributions to help establish a makerspace. He sought to leverage his contacts and networks to obtain physical resources. An example was a large plasma screen, donated by one of the makerspace members, which is used infrequently, but available just in case it is needed:

> *"...we're not using it all the time. It's basically off for maybe months at a time. but you know, at least when we do have a presentation, we have a good big plasma screen" (George).*

Physical resources in makerspaces include the tools such as 3DP, but also furniture, other equipment, and the physical spaces in which they operate. These are often obtained through donations or voluntary contributions since funds are limited. Bricolage can be seen in the way participants actively look for resources, even if they do not immediately have a use for them. This is necessary in makerspaces such as Innov8, which has relatively low fees to cover costs, and MakersLabs, which does not charge for access. Both makerspaces aim to be very open in the access they provide, and who they provide it to. In contrast, UniLabs and MakerStart appeared less chaotic and more organised because they restrict access to university members or paying customers, respectively. Their approach to accumulating resources is therefore more planned, purchasing equipment where there is expected demand, and maintaining these resources more rigorously.

4.2.2 Information

Just like physical resources, information resources are openly shared among makerspace members. Indeed, given the role of digital fabrication, in which computer files can be shared and transformed into physical objects, the boundaries are blurred between physical and information resources. There seems to be a collective responsibility to make information widely available to other makerspace members. Unlike proprietary software and hardware, which may be 'closed' in the sense that modifying and reusing them is restricted, makerspace members generally aim for openness in their projects. Openness can be seen as an essential part of democratising innovation and central to the objectives of makerspaces:

> *"I am keen in working where IP is shared and not restricted …anybody can just, you know, download something from the web… and put it into a 3D printer and then they have a physical thing. They don't need to depend on a manufacturing company to design or do something…" (George)*

Having this in mind, makerspace members share information and expect that others will do likewise, for mutual benefit. Even though most individuals in the makerspaces we investigated were working on their own individual projects, they were normally ready to support others by sharing information. People in makerspace are perhaps as important as the tools are. A makerspace is "just a space where there's stuff and you can do things, but it was also just weird [when it is] empty, with no one there" (David). Without people to interact with, share ideas with and obtain information from, a makerspace is of limited value.

4.2.3 Skills

In addition to sharing their information and ideas, makerspace members also support each other by openly offering their skills to others. All makerspace members have some expertise, knowledge, or base of ideas. Yet all of them have gaps that they seek to fill and to support others to fill. 3DP, which combines mechanical, electronic, software and materials engineering illustrates this. While makerspace members are proficient in some of the required skills, they are often uncomfortable with others. Alan and Brian discussed their own gaps in knowledge, their attempts to overcome these by meeting people in MakersLab, and examples of their efforts to help others. For example, Alan explained how he used 3DP to create objects for others. These include gifts for his wife, but also designing and making the part shown in Figure 3, for his neighbour.

> *"[the neighbour is] very old, got arthritic hands, you know, while the taps on a radiator are like very small things. He couldn't turn it… so I made a large radiator top*

for him that would fit over… what you would want ideally was a handle that big that you can easily get hold of but because the valve is really close to the side of the radiator, you're limited to something that big, so I made a hexagonal top that he could turn" (Alan)

Insert Figure 3 here

In this example, Alan has followed a rigorous product development process, interacting with the user and customising the design to fit the requirements. In doing so, he finds an opportunity to gain experience and learn about the technology, and he happily shares this knowledge with other makerspace members in the interests of serving the community.

Meanwhile, Brian takes on the role of repairing and maintaining equipment, both to give himself an objective, and to remove barriers for others.

> *"I can't do the designs [of models to be 3D printed] and so I'm not really confident, but with the printers, I've messed around with them long enough to know roughly how to repair them, So I feel like I go there and I have a goal: to try and get all the printers working. 'Cause then everyone else can print their stuff".* (Brian)

Open access to equipment is clearly important for makerspace members, so maintaining the equipment is a collective responsibility.

4.2.4 Processes

The benefits of bricolage, and of openness, are revealed in the ease with which resources are shared and accessed across a community of likeminded people. For someone who sees making as a hobby, a makerspace is an ideal place to learn or be creative. Yet the drawbacks are revealed when they seek to take a hobby further.

A community of people that insist on open access and collective responsibility can find itself with no one taking responsibility for important duties. Unlike a more professional environment, if processes are not established and duties unclear a makerspace may become difficult to work in. For Charlie, David and Eric, the absence of processes became problematic when they sought to develop their ideas into a commercially viable product. Firstly, they realised they needed to be stricter in their own division of responsibilities to concentrate on key areas such as client management and product development. Secondly, they needed to find a space to work that was less open, or at least more organised. They described a makerspace where they could not work effectively:

> *"[the makerspace was] a really cheap space where we could work, as in desk space, and also have access to tools and I guess a bit of knowledge, or technicians….we left after a week…the equipment was terrible, the safety was questionable for a lot of stuff, I don't know, things like the table saw…the ventilation…" (Eric)*

In this case bricolage can be implicated in safety standards being overlooked, while people focus on achieving a goal. This resembles the motorcycle repair shop studied by Baker and Nelson (2005) where the only safety rule seemed to be a ban on pyrotechnics, due to a previous fire in the uninsured building. In contrast, MakerStart offered a more professional working environment, with fewer safety concerns. "…you have people that are actually accountable or responsible for the space, the workshops, the machines…" (Eric). In some ways the enterprise outgrows the makerspace and there is a need to establish processes, moving away from bricolage to achieve commercial growth.

For the makerspace members we studied, open access to resources is important and this demands collective responsibility. The benefits of bricolage are evident in the way that shared resources; and they are accumulated and adapted to suit demands as they emerge. Yet the drawbacks of bricolage emerge when participants see what they do as work and not a pastime, or as business not voluntary work. Openness to new ideas, generating solutions to problems, and often altruistic sharing behaviours may be useful for finding creative solutions to challenges. Yet they also restrict growth, as in makerspaces where the ad-hoc collection of resources and the lack of clear responsibility for their maintenance can be unproductive. For this reason, Jim encourages makers who see themselves as entrepreneurs to learn by working in an industry, while continuing to develop their ideas and prototypes, rather than spend all their time as bricoleurs in makerspaces. As he put it, “being an entrepreneur and getting a job is not a failure”. Instead, working in a professional environment exposes makers to the processes they need to adopt if they are to go beyond making do and be able to scale up their ideas.

5. Discussion and conclusions

We set out to better understand individuals’ propensity to engage with emerging technologies, in this case 3DP, in a do-it-yourself manner, and what part makerspaces might play in democratising innovation. We explored the topic empirically to understand why and how 3DP technologies are used, and how individuals reflect on their engagement within makerspaces. We identified bricolage as a useful lens through which to examine the motivation and behaviour of makerspace members. Bricolage has been widely applied to analysis of entrepreneurs in general (Baker et al., 2003; Baker and Nelson, 2005; Vanevenhoven et al., 2011) but also digital innovation (Rüling and Duymedjian, 2014) and, to a lesser extent, innovation in makerspaces (Suire, 2019).

We extend the understanding of entrepreneurial bricolage by drawing on the open source innovation literature and combining the two. In doing so, we find a range of reasons why people innovate in a do-it-yourself context, from curiosity to community duty to commercial motives. We also demonstrate the mechanisms by which they innovate, showing how makerspaces create opportunities for resource sharing and 3DP helps to realise innovation outcomes. What distinguishes the results from previous empirical work on bricolage is the focus on 3DP, which emerges as a tool to enable bricolage.

In line with prior studies of makerspaces (Davies, 2018), we found most individuals to be focused on their own interests, and that the objectives in general are far more mundane than revolutionary rhetoric might suggest (Anderson, 2012; D’Aveni, 2015; Rigi, 2013). We found entrepreneurial ambitions, at least in the sense of turning hobbies into earnings, to be part of the motivation for some participants. Such ambitions were either realised, for Charlie, David and Eric, or at least a nascent idea for example for Harry and Ian. The idea that anyone can innovate (Cruickshank, 2014), that digital tools are available to everyone (Woodson et al., 2019), and that individuals do not need to rely on companies, comes through in the actions as well as words of the makerspace members we studied. Democratisation is evident, whether it is part of a political plan or not, or simply based on individuals' action.

5.1 How makerspace members innovate

Bricolage describes the approach of making do with whatever resources are at hand, as opposed to seeking the optimal, but often unattainable, ones. Makerspaces contribute to this by offering free or subsidised shared access to resources, particularly fabrication tools, of which our focus in this study was 3DP. The impact of such tools can be summed up as follows.

> *"3D printing is kind of like what Punk was for music or what WordPress was for web development… it used to be that you needed to learn a lot about HTML CSS and JavaScript to set up a website. But now all you need to do is just point and click…to create your own website and easy tutorials to follow or drop-down menus… democratising manufacturing now that does not mean that it will be a better quality... but most of the time it's enough for a fabrication process." (George)*

The significance of punk in this context is not the aesthetics or sound, but the do-it-yourself attitude that the music inspired. For example, the early punk rock bands in the UK, in the 1970s, are said to have inspired others to form bands or create independent record labels. This includes avoiding "the capitalist, profit-driven music world by promoting their bands, shows, and records themselves or through small companies" (Haenfler, 2006, p.24). Just as such bands sacrificed (or deliberately avoided) virtuosity in favour of independence, making products with 3DP often means sacrificing quality. Several participants in our study pointed out that 3DP had allowed them to create things they otherwise could only have considered in theory. Yet the limits of their bricolage restrict the extent to which their innovations achieve commercial success. The limits are both in terms of their status as amateurs who lack certain skills and experience, and the restrictions of the low-cost 3DP tools they have access to. The implication is that, as with the music industry, creativity may originate from do-it-yourself bricolage, but processes must be created, and resources obtained to achieve commercial outcomes.

This research provides evidence of how makerspaces and 3DP can contribute to this process. We found several instances of 3DP used to enable bricolage. Rather than printing whole products, participants recognised its value is in printing only the parts that cannot be readily obtained. The same can be seen in the printers themselves, for example open source 3D printers, such as RepRap (Raasch et al., 2009), which combine cheap components like motors, cables and screws with custom designed plastic components. Much has been made of the so-called 3DP revolution (D'Aveni, 2015), but predictions that it will disrupt manufacturing have been made since the late 1980s (Beltagui et al., 2020b) and have yet to materialise. By examining how makerspace members apply 3DP, we suggest that these tools will complement, rather than replace manufacturing processes. The complementary nature has important implications for the understanding of these technologies and for investments by companies, individuals and communities. For do-it-yourself innovation, 3DP is incredibly useful because it makes it feasible to design and create working products through bricolage. On the other hand, we see several instances in which bricolage seems to restrict development or limit scale up and commercialisation.

Baker and Nelson (2005) identified bricolage as a valuable process carried out by entrepreneurs, who often disregard institutional or regulatory restrictions, taking a pragmatic approach to getting things done. While this works well in the short term, for example in meeting the needs of one customer, it may be limiting in the longer term. For example, Senyard et al's (2014) finding of a curvilinear relationship between bricolage and innovation performance suggests the initial benefits for new firms give way to a barrier to growth. An explanation is that organisational processes and routines capture what has been learned from solving problems, to allow such problems to be overcome more efficiently (Beltagui, 2018). In essence, a lack of such processes offers freedom for the bricoleur, but could equally leave them constantly re-inventing the wheel; therefore, makerspaces should build the capacity to be able to advise bricoleurs on the work taking place in existing innovative clusters (e.g. in this case regarding 3DP) in order to contribute to a sustainable innovation ecosystem (Suire, 2019). This leads to the following propositions that can guide future investigations:

> *P1: Makerspace members innovate by combining readily available resources, using 3DP to fill gaps and make connections.*

> *P2: Makerspace members are open to gathering and combining resources – including physical, information and skills – and expect other participants to reciprocate.*

5.2 Why makerspace members use 3DP to innovate

The present study presents evidence that makerspace members use 3DP to innovate through bricolage. The other element of our research question concerns *why* they do so.

Exploring participants' backgrounds and reasons for joining makerspaces revealed childhood memories of making, or of exploring physical objects and how they work. Anderson (2012) argues that everyone used to be a maker until digital technologies became the norm. He recounts tales of summers spent in a workshop with his grandfather, inventing and making, before he began using computers and making with a keyboard rather than a lathe. Similarly, we found makerspace members readily thinking back to childhood memories that sparked their interest in making. Whether this was from playing with construction toys or watching a Grandfather at work, these memories seemed to inspire a desire that could be realised through 3DP. All of the participants we interviewed demonstrated some desire to be creative, to learn new skills or to develop their understanding. Yet in most cases this did not translate into commercial innovations. Indeed, as highlighted in the literature (Halbinger, 2018; West and

Kuk, 2016), makers may be ideologically opposed to the idea that their creativity should be commercialised. None of the participants in our study admitted to starting out with entrepreneurial intentions, although some, such as Harry, showed an interest in getting paid for something they enjoyed.

Again, the role of bricolage may be important in understanding the motivations makerspace members. (Stinchfield et al., 2013) compared entrepreneurs adopting bricolage, to those adopting other categories of activity identified by Lévi-Strauss, such as art, craft and engineering. They showed that the bricoleur was less likely to achieve commercial success, even if they could often be more creative in solving problems than the craftsperson or engineer. Similarly, in our study, Jim recounted an example of makers who raised investment for a product but spent more to deliver it than they were paid. He explained that they were happy with the achievement of making and selling a product, as bricoleurs might be, but failed to break-even because they failed to plan structured processes in advance, as 'ingenieurs' might be expected to. What the literature does not necessarily make clear is how flexible these roles are in the context of entrepreneurship. In the present study, we see examples of bricoleurs, whose motivation seems to be almost entirely altruistic or exploratory, and those who may have adopted such an approach in the past but now see its limitations. In this vein, the lack of managerial guidelines and the absence of a robust set of good practices has been highlighted (Suire, 2019). A fruitful topic for further investigation may be to understand how makers can leave behind the bricolage that helps them create, in favour of a more structured process that helps them innovate. The following propositions call for further investigating creativity and commercialising innovation through the lens of bricolage:

P3: Makerspace members fulfil their desire to be creative using 3DP by adopting a bricolage approach.

P4: Makerspace members gradually reduce their reliance on both bricolage and

3DP in order to achieve commercial success.

5.3 Theoretical contributions

This study of 3DP use in makerspaces makes a number of important contributions to theory. Firstly, it exemplifies the role of do-it-yourself labs and digital fabrication tools in supporting individuals' desire for creativity and innovation. Specifically, it positions these labs in relation to in-house or outsourced R&D and crowdsourcing. Where problems and their solutions are known in advance, the traditional role of R&D is to refine products that deliver on scientific discoveries. For example, drug discovery leads to R&D that focuses on creating a drug delivery mechanism. The latter is likely to be most efficiently carried out by in-house or outsourced R&D teams that are specialised and focused. Where problems are defined, but their solutions are speculative, crowdsourcing seems like a valuable approach that distributes the challenge and invests resources only when a solution is achieved. Yet for problems that are not defined in advance, makerspaces may offer a useful approach. Examples from the present study, which may not have been identified by companies, include radiator handles for those suffering from arthritis, automated gear shift for cyclist in hilly areas, or indeed remote monitoring of climatic conditions in farming areas. Makerspaces allow individuals to explore such problems, with minimal investment, while 3DP helps them transform their concepts and ideas into working prototypes and products. Von Hippel (2005) argues that companies should not only recognise the contributions users can make, but also facilitate contributions through toolkits that make innovation more democratic. We add to this argument by highlighting the important role that makerspaces can play by providing tools, and 3DP by allowing people to make almost anything they can imagine (Gershenfeld, 2012). Both makerspaces and 3DP may support democratising innovation by empowering citizens to turn their ideas into reality.

Secondly, the research identifies bricolage as a promising lens through which to study makerspaces and makerspace communities. Research has demonstrated that bricolage is important for resource-constrained situations. While researchers have applied bricolage perspectives to entrepreneurship (Baker and Nelson, 2005) and to service management (Wittell et al., 2017), this research provides a novel application to innovation that takes place outside of the influence of companies and to a specific technology. We see the role of 3DP as enabling synergy in the sense that physical resources are combined more effectively. Nonetheless the role of makerspaces goes further. These spaces rely on bricolage to build resources, which are accumulated opportunistically rather than strategically. The openness they rely on means that physical resources as well as social and intellectual capital are made available, further enabling bricolage. Innovating in this context is therefore something that appeals to the bricoleur but may not be feasible for others.

Thirdly, the research highlights that while 3DP enables bricolage, it rarely replaces other manufacturing methods. Based on our results, makerspaces seem unlikely to directly disrupt established companies. One notable observation in the present study was how few makerspace members were using 3DP. Many more were observed in each makerspace than those interviewed, who were the most active 3DP users. This supports the finding that 3DP has a more limited, but vital, role as an enabler of bricolage, by allowing connections to be made between components of products. 3DP’s ability to connect or fill gaps in resources should not be underestimated – several participants stated that their innovations could not have been realised without 3DP. Still the adoption of 3DP should also not be overestimated – perhaps not every home will have a 3D printer and not every product will be produced by 3DP in the near future.

5.4 Implications for practice

This study, exploring a possible route to democratising innovation, offers valuable insights to both makerspace members, seeking to innovate, but also to managers of firms that may seek to support commercialisation of the innovations.

Firstly, for makerspace members, we observe differences in the range of available makerspaces, such that selecting the most suitable environment is vital. Some emphasise exploration (e.g.

MakersLab), while others are more geared to commercialisation (e.g. MakerStart). In all cases, openness to sharing resources, information and skills with others is crucial as this enables bricolage, largely agreeing with Suire (2019).

Makerspace members benefit from adopting a bricolage approach that focuses on creating synergy between resources. In this respect, learning to use tools such as 3DP is helpful because it supports the ability to turn collections of physical resources into functioning products that solve problems as they are identified. Yet makerspace members may change their objectives, particularly if their commercial ambitions grow as they develop products and seek to profit from their creations. This may mean leaving behind the environment of the makerspace, along with bricolage. There is some evidence that seeking profit, especially if it means restricting access to ideas, is at odds with the openness to sharing exhibited by makers. For example, Davies (2018) argues that business incubators rely less on openness and community than makerspaces because they are seen as a means to an end. In contrast, many go to makerspaces without a clear end goal in mind, just a place to be creative or meet likeminded people. Balancing their creative and commercial ambitions is important and should encourage makers to consider the extent to which they should maintain the approach of the 'bricoleur' or 'ingenieur'.

Makerspaces may be an important driver of economic development, especially at a local level (van Holm, 2017). Firms may see them as an irrelevance, since there are few visible examples of highly successful product innovations, comparable to open source software innovations. Or makerspaces may represent a threat since they allow potentially disruptive products to be developed – if not manufactured – outside of the visibility of a firm's industry. Alternatively, in line with von Hippel's (2005) idea of democratising innovation, we suggest that firms should see makerspaces as an important source of innovations and look at ways to create partnerships between makers and producers. There is evidence that sponsored makerspaces produce innovations as well as allowing professionals to explore creative ideas (Svensson and

Hartmann, 2018). Care must be taken to understand the cultural implications. While would-be innovators would appreciate support, bricoleurs – who work well in resource-constrained environments – may be suspicious of commercial interests (Davies, 2018; Haenfler, 2006). The challenge, therefore, is to avoid restricting openness (West and Kuk, 2016) at the early stages of innovation, while offering support when makers are prepared to reduce their reliance on bricolage in order to scale up production and commercial activity. Comparison with software development, in which start-ups seek to develop applications with the aim of selling IP may become more relevant in future.

5.5 Limitations and future work

A number of limitations can be identified, which also suggest avenues for further research. Firstly, the study focuses specifically on 3DP use in makerspaces, and on the lived experience of participants. It therefore says little about the similarities and differences between 3DP users and other makerspace members. It is likely that the ethics and practices are closely related. For example, since comparisons can be seen with open source software development, it is highly likely that 3DP users are not unique. Nonetheless, it is not clear how widely the results can be generalised, to other contexts, for example bio-hacking, and other technologies. The propositions should therefore be tested, evaluated and extended through further research.

Secondly, a notable feature of the sample is that all of the individuals who met the inclusion criteria – i.e. were observed using 3DP multiple times in a makerspace – were male. This was not deliberate, but is also not surprising, given the demographics of most makerspaces (Davies, 2018; Richterich, 2018). For innovation to truly be democratic, it must be accessible to all. There is no suggestion that the makerspaces we investigated or the participants we interviewed would disagree with this. Yet further research that gives voice to underrepresented groups is essential.

Thirdly, the study suggests there are differences between different makerspaces, for example those whose members are interested in learning and exploration compared with those who are more commercially driven. A fruitful avenue for further study would be an explicit classification or typology of makerspaces. This would help both researchers and innovators to focus their attention.

Finally, we highlight that bricolage helps innovation and exploration while hindering growth and exploitation. We see this through a series of snapshots, from individuals at various stages in the innovation process. Such snapshots can be connected by systematically examining the lifecycle of innovations and innovators, to understand whether and how bricolage is used, as an individual goes from being a maker to becoming an entrepreneur. Indeed, our focus here on innovation means there are limited examples of entrepreneurship. Future research should investigate entrepreneurs specifically, to understand whether entrepreneurs who 'graduated' from makerspaces and use 3DP have similar identities and motivations and successes to other entrepreneurs.

6. References

Adamides, E., Karacapilidis, N., 2020. Information technology for supporting the development and maintenance of open innovation capabilities. *Journal of Innovation & Knowledge*, *5*(1), 29-38. https://doi.org/10.1016/j.jik.2018.07.001

Aitamurto, T., Holland, D., Hussain, S., 2015. The open paradigm in design research. Design Issues, 31, 17–29. https://doi.org/10.1162/DESI_a_00348

Anderson, C., 2012. Makers: the new industrial revolution. Random House, New York, NY.

Baker, T., Miner, A.S., Eesley, D.T., 2003. Improvising firms: bricolage, account giving and improvisational competencies in the founding process. Research Policy 32, 255–276. https://doi.org/10.1016/S0048-7333(02)00099-9

Baker, T., Nelson, R.E., 2005. Creating something from nothing: Resource construction through entrepreneurial bricolage. Administrative Science Quarterly 50, 329–366. https://doi.org/10.2189/asqu.2005.50.3.329

Baumers, M., Holweg, M., 2019. On the economics of additive manufacturing: Experimental findings. Journal of Operations Management 65, 794–809. https://doi.org/10.1002/joom.1053

Beltagui, A., 2018. A design-thinking perspective on capability development: The case of new product development for a service business model. International Journal of Operations and Production Management 38, 1041–1060. https://doi.org/10.1108/IJOPM- 11-2016-0661

Beltagui, A., Kunz, N., Gold, S., 2020a. The role of 3D printing and open design on adoption of socially sustainable supply chain innovation. International Journal of Production Economics 221. https://doi.org/10.1016/j.ijpe.2019.07.035

Beltagui, A., Rosli, A., Candi, M., 2020b. Exaptation in a digital innovation ecosystem: The disruptive impacts of 3D printing. Research Policy 49. https://doi.org/10.1016/j.respol.2019.103833

Bogers, M., Hadar, R., Bilberg, A., 2016. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. Technological Forecasting and Social Change 102, 225–239. https://doi.org/10.1016/j.techfore.2015.07.024

Brabham, D.C., 2008. Crowdsourcing as a model for problem solving: An introduction and cases. Convergence 14, 75–90. https://doi.org/10.1177/1354856507084420

Brown, T., Martin, R., 2015. Design for Action: how to use design thinking to make great things actually happen. Harvard Business Review 93, 57–64.

Candi, M., Beltagui, A., 2019. Effective use of 3D printing in the innovation process. Technovation 80–81, 63–73. https://doi.org/10.1016/j.technovation.2018.05.002

Chambers, E., 2003. Applied Ethnography, in: Denzin, N.K., Lincoln, Y.S. (Eds.), Collecting and Interpreting Qualitative Materials. Sage, Thousand Oaks, CA, pp. 389–419.

Chesbrough, H., Cohen, W.M., Levinthal, D. a, Felin, T., Zenger, T.R., Gassmann, O., Enkel, E., Chesbrough, H.W., Hislop, D., von Hippel, E., Cheng, C.C.J., Huizingh, E.K.R.E., Chesbrough, H.W., Appleyard, M.M., Euchner, J., Remneland Wikhamn, B., Wikhamn, W., Casadesus-Masanell, R., Almirall, E., Lichtenthaler, U., West, J., Gallagher, S., 2010. Open Versus Closed Innovation, Research-Technology Management. https://doi.org/10.1111/j.1467-9310.2006.00436

Chesbrough, H.W., 2003. The Era of Open Innovation. MIT Sloan Management Review 44 (3), 35–41.

Cruickshank, M.L., 2014. Open Design and Innovation: facilitating creativity in everyone. Gower Publishing.

D'Aveni, R.A., 2015. The 3-D Printing Revolution. Harvard Business Review 93, 41–48.

Davies, S.R., 2018. Characterizing Hacking: Mundane Engagement in US Hacker and Makerspaces. Science Technology and Human Values 43, 171–197. https://doi.org/10.1177/0162243917703464

Davis, J. R., Richard, E. E., & Keeton, K. E. 2015. Open innovation at NASA: A new business model for advancing human health and performance innovations. *Research-Technology Management*, *58*(3), 52-58. https://doi.org/10.5437/08956308X5803325

de Jong, J.P.J., de Bruijn, E., 2013. Innovation Lessons From 3-D Printing. MIT Sloan Management Review 54, 43–52. https://doi.org/10.3402/meo.v20.29847

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S.J., Garmulewicz, A., Knowles, S., Minshall, T.H.W., Mortara, L., Reed-Tsochas, F.P., Rowley, J., 2017. Unlocking value for a circular economy through 3D printing: A research agenda. Technological Forecasting and Social Change 115, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Dorst, K., 2011. The core of "design thinking" and its application. Design Studies 32, 521–532. https://doi.org/10.1016/j.destud.2011.07.006

Dubois, A., Gadde, L.-E., 2002. Systematic combining: an abductive approach to case research. Journal of Business Research 55, 553–560. https://doi.org/10.1016/S0148-2963(00)00195-8

Duymedjian, R., Rüling, C.C., 2010. Towards a foundation of bricolage in organization and management theory. Organization Studies 31, 133–151. https://doi.org/10.1177/0170840609347051

Eitzel, M.V., Cappadonna, J.L., Santos-Lang, C., Duerr, R.E., Virapongse, A., West, S.E., Kyba, C., Bowser, A., Cooper, C.B., Sforzi, A. and Metcalfe, A.N., 2017. Citizen science terminology matters: exploring key terms. *Citizen science: Theory and practice*, 2(1). http://doi.org/10.5334/cstp.96

Evered, R., Louis, M.R., 1981. Alternative Perspectives in the Organizational Sciences: "Inquiry from the Inside" And "Inquiry from the Outside." Academy of Management Review 6, 385–395. https://doi.org/10.5465/amr.1981.4285776

Gassmann, O., 2006. Opening up the innovation process: towards an agenda. *R&D Management*, *36*(3), 223-228. 10.1111/j.1467-9310.2006.00437.x

Gershenfeld, N., 2012. How to make almost anything: The digital fabrication revolution. Foreign Affairs 91, 43-57.

Golden-Biddle, K., Locke, K., 1993. Appealing Work: an investigation of how ethnographic texts convince. Organization Science 4, 595–616. https://doi.org/10.1287/orsc.4.4.595

Guba, E.G., Lincoln, Y.S., 2005. Paradigmatic controversies, contradictions and emerging confluences, in: Denzin, N., Lincoln, Y.S. (Eds.), The Sage Handbook of Qualitative Research. Sage, Thousand Oaks, CA, pp. 191–215.

Haenfler, R., 2006. Straight Edge; Hardcore Punk, Clean Living Youth, and Social Change.

Rutgers University Press, New Jersey.
Halbinger, M.A., 2018. The role of makerspaces in supporting consumer innovation and diffusion: An empirical analysis. Research Policy 47, 2028–2036. https://doi.org/10.1016/j.respol.2018.07.008
Hargadon, A., Sutton, R.I., 1997. Technology Brokering and Innovation in a Product Development Firm, Administrative Science Quarterly. https://doi.org/10.2307/2393655
Hindle, K., Yencken, J., 2004. Public research commercialisation, entrepreneurship and new technology based firms: an integrated model. *Technovation*, 24(10), 793-803. https://doi.org/10.1016/S0166-4972(03)00023-3
Hollands, R.G., 2015. Critical interventions into the corporate smart city. Cambridge Journal of Regions, Economy and Society 8, 61–77.
Howe, J., 2006. The Rise of Crowdsourcing. Wired 14.
Hunsinger, J., Schrock, A., 2016. The democratization of hacking and making. New Media & Society 18, 535–538. https://doi.org/10.1177/1461444816629466
Kerr, W.R., Nanda, R., Rhodes-Kropf, M., 2014. Entrepreneurship as experimentation. Journal of Economic Perspectives 28, 25–48. https://doi.org/10.1257/jep.28.3.25
Khajavi, S.H., Partanen, J., Holmström, J., 2014. Additive manufacturing in the spare parts supply chain. Computers in Industry 65, 50–63. https://doi.org/10.1016/j.compind.2013.07.008
Kline, S.J., Rosenberg, N., 1986. An Overview of Innovation, in: Landau, R., Rosenberg, N. (Eds.), The Positive Sum Strategy. National Academy Press., Washington, DC.
Lakhani, K.R., von Hippel, E., 2003. How open source software works: “free” user-to-user assistance. Research Policy 32, 923–943. https://doi.org/10.1016/S0048-7333(02)00095-1
Langley, D. J., Zirngiebl, M., Sbeih, J., & Devoldere, B. 2017. Trajectories to reconcile sharing and commercialization in the maker movement. *Business Horizons*, *60*(6), 783-794. https://doi.org/10.1016/j.bushor.2017.07.005
Lévi-Strauss, C., 1966. The savage mind (La pensée sauvage) English translation. Weidenfeld and Nicolson, London.
Malhotra, A., Majchrzak, A. (2014). Managing crowds in innovation challenges. *California Management Review*, *56*(4), 103-123. https://doi.org/10.1525/cmr.2014.56.4.103
Mortara, L, Parisot, N., 2016a. How Do Fab-Spaces Enable Entrepreneurship? Case Studies of “Makers” Entrepreneurs. International Journal of Manufacturing Technology and Management 32, 16–42. https://doi.org/10.2139/ssrn.2519455

Mortara, Parisot, N., 2016b. Through entrepreneurs' eyes: the Fab-spaces constellation. International Journal of Production Research 54, 7158–7180. https://doi.org/10.1080/00207543.2016.1198505

Moultrie, J., Livesey, F., Malvido, C., Beltagui, A., Pawar, K., Riedel, J., 2009. Design Funding in Firms: A Conceptual Model of the Role of Design in Industry1. Design Management Journal 4, 68–82. https://doi.org/10.1111/j.1942-5074.2009.00008.x

Nambisan, S., 2017. Digital Entrepreneurship: Toward a Digital Technology Perspective of Entrepreneurship. Entrepreneurship: Theory and Practice 41, 1029–1055. https://doi.org/10.1111/etap.12254

Nambisan, S., Baron, R.A., 2009. Virtual Customer Environments: Testing a Model of Voluntary Participation in Value Co-creation Activities. Journal of Product Innovation Management 26, 388–406. https://doi.org/10.1111/j.1540-5885.2009.00667.x

Poetz, M.K., Schreier, M., 2012. The value of crowdsourcing: Can users really compete with professionals in generating new product ideas? Journal of Product Innovation Management 29, 245–256. https://doi.org/10.1111/j.1540-5885.2011.00893.x

Raasch, C., Herstatt, C., Balka, K., 2009. On the open design of tangible goods. R and D Management 39, 382–393. https://doi.org/10.1111/j.1467-9310.2009.00567.x

Rank, J., Pace, V. L., & Frese, M. 2004. Three avenues for future research on creativity, innovation, and initiative. *Applied psychology*, *53*(4), 518-528. https://doi.org/10.1111/j.1464-0597.2004.00185.x

Rayna, T., Striukova, L., 2016. From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. Technological Forecasting and Social Change 102, 214–224. https://doi.org/10.1016/j.techfore.2015.07.023

Rerup, C., 2015. "Houston We Have a Problem": Anticipation and Improvisation as Sources of Organizational Resilience. Comportanmento Organizacional E Gestão 7, 27–44.

Richterich, A., 2018. Tracing controversies in hacker communities: ethical considerations for internet research 23, 76–93. https://doi.org/10.1080/1369118X.2018.1486867

Rigi, J., 2013. Peer production and Marxian communism: Contours of a new emerging mode of production. Capital and Class 37, 397–416. https://doi.org/10.1177/0309816813503979

Rindfleisch, A., O'Hern, M., Sachdev, V., 2017. The Digital Revolution, 3D Printing, and Innovation as Data. Journal of Product Innovation Management 34, 681–690. https://doi.org/10.1111/jpim.12402

Rothwell, R., 1992. Successful Industrial Innovation: Critical Factors for the 1990s. R&D Management 22, 221–239. https://doi.org/10.1111/j.1467-9310.1992.tb00812.x

Rüling, C.C., Duymedjian, R., 2014. Digital bricolage: Resources and coordination in the production of digital visual effects. Technological Forecasting and Social Change 83, 98–110. https://doi.org/10.1016/j.techfore.2013.05.003

Sandström, C.G., 2016. The non-disruptive emergence of an ecosystem for 3D Printing - Insights from the hearing aid industry's transition 1989-2008. Technological Forecasting and Social Change 102, 160–168. https://doi.org/10.1016/j.techfore.2015.09.006

Sarpong, D., Ofosu, G., Botchie, D. and Clear, F., 2020. Do-it-yourself (DiY) Science: The proliferation, relevance and concerns, Technological Forecasting and Social Change https://doi:10.1016/j.techfore.2020.120127

Sarpong D., Rawal, A., 2020. From the open to DiY laboratories: Managing innovation within and outside the firm, In Fritzsche A (Eds.), Innovating in the Open Lab: The New Potential for Interactive Value Creation across Organizational Boundaries, (Eds.) Fritzsche, A, Jonas, JM, Roth A and Möslein KM, De Gruyter Studies in Innovation and Entrepreneurship https://doi: 10.1515/9783110633665-023

Schniederjans, D.G., 2017. Adoption of 3D-printing technologies in manufacturing: A survey analysis. International Journal of Production Economics 183, 287–298. https://doi.org/10.1016/j.ijpe.2010.07.039

Schot, J., Steinmueller, W. E., 2018. Three frames for innovation policy: R&D, systems of innovation and transformative change. *Research Policy*, *47*(9), 1554-1567. https://doi.org/10.1016/j.respol.2018.08.011

Seltzer, E., Mahmoudi, D., 2013. Citizen Participation, Open Innovation, and Crowdsourcing: Challenges and Opportunities for Planning. Journal of Planning Literature 28, 3–18. https://doi.org/10.1177/0885412212469112

Senyard, J., Baker, T., Steffens, P., Davidsson, P., 2014. Bricolage as a path to innovativeness for resource-constrained new firms. Journal of Product Innovation Management 31, 211–230. https://doi.org/10.1111/jpim.12091

Sichel, D., von Hippel, E., 2019. Household Innovation, R&D, and New Measures of Intangible Capital, working paper.

Simon, H.A., 1973. The Structure of Ill Structured Problems. Artificial Intelligence 4, 181–201. https://doi.org/10.1016/0004-3702(73)90011-8

Stinchfield, B.T., Nelson, R.E., Wood, M.S., 2013. Learning From Levi-Strauss' Legacy: Art, Craft, Engineering, Bricolage, and Brokerage in Entrepreneurship.

Entrepreneurship: Theory and Practice 37, 889–921. https://doi.org/10.1111/j.1540-6520.2012.00523.x

Strauss, A., Corbin, J., 1998. Basics of qualitative research techniques. Sage, Thousand Oaks, CA.

Suire, R., 2019. Innovating by bricolage: how do firms diversify through knowledge interactions with FabLabs? Regional Studies 53, 939–950. https://doi.org/10.1080/00343404.2018.1522431

Surowiecki, J., 2005. The wisdom of crowds, why the many are smarter than the few and how collective wisdom shapes business, economies, societies and nations. Anchor Books, New York, NY.

Sutton, R.I., Hargadon, A., 1996. Brainstorming Groups in Context: Effectiveness in a Product Design Firm, Source: Administrative Science Quarterly. https://doi.org/10.2307/2393872

Svensson, P.O., Hartmann, R.K., 2018. Policies to promote user innovation: Makerspaces and clinician innovation in Swedish hospitals. Research Policy 47, 277–288. https://doi.org/10.1016/j.respol.2017.11.006

van Abel, B., Evers, L., Klaasen, R., Troxler, P., 2010. Open design now: why design cannot remain exclusive. BIS Publishers, Amsterdam.

van Holm, E.J., 2017. Makerspaces and Local Economic Development. Economic Development Quarterly 31, 164–173. https://doi.org/10.1177/0891242417690604

Vanevenhoven, J., Winkel, D., Malewicki, D., Dougan, W.L., Bronson, J., 2011. Varieties of bricolage and the process of entrepreneurship. New England Journal of Entrepreneurship 14, 53–66. https://doi.org/10.1108/neje-14-02-2011-b005

von Hippel, E., 2005. Democratizing innovation. MIT Press, Cambridge, MA.

von Hippel, E., von Krogh, G., 2003. Open Source Software and the “Private-Collective” Innovation Model: Issues for Organization Science. Organization Science 14, 209–223. https://doi.org/10.1287/orsc.14.2.209.14992

Von Stamm, B. (2008). *Managing innovation, design and creativity*. John Wiley & Sons.

Walter-Herrmann, J., 2013. FabLabs-a global social movement?, in: Walter-Hermann, J., Büching, C. (Eds.), Fablab: Of Machines, Makers and Inventors. Verlag, Bielefeld, Germany.

Weller, C., Kleer, R., Piller, F.T., 2015. Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. International Journal of Production Economics 164, 43–56. https://doi.org/10.1016/j.ijpe.2015.02.020

West, J., Kuk, G., 2016. The complementarity of openness: How MakerBot leveraged Thingiverse in 3D printing. Technological Forecasting and Social Change 102, 169–

181. https://doi.org/10.1016/j.techfore.2015.07.025

Witell, L., Gebauer, H., Jaakkola, E., Hammedi, W., Patricio, L., Perks, H., 2017. A bricolage perspective on service innovation. Journal of Business Research 79, 290–298. https://doi.org/10.1016/j.jbusres.2017.03.021

Woodson, T., Alcantara, J.T., do Nascimento, M.S., 2019. Is 3D printing an inclusive innovation?: An examination of 3D printing in Brazil. Technovation 80–81, 54–62. https://doi.org/10.1016/j.technovation.2018.12.001

Wu, C. H., Parker, S. K., & De Jong, J. P., 2014. Need for cognition as an antecedent of individual innovation behavior. *Journal of Management*, *40*(6), 1511-1534. https://doi.org/10.1177/0149206311429862

Appendix 1 – Semi-structured interview questions

1	When did you start using 3d printing technologies?
2a	What are the reasons you first got engaged with 3d printing technologies? (Can you support your reply by giving some specific examples)?
2b	Have these reasons changed since you first started with 3d printing?
3	In which part of the 3d printing/additive manufacturing process do you specialise?
4	Please refer to a 3d printing output you have put together lately and discuss about your lived experience as it naturally occurred in your interactions with the 3d printing devices and environment/lab where this took place.
5a	How do you expect 3d printing technologies will affect the interactions between humans and machines?
5b	How do you expect 3d printing technologies will affect the business and social interactions between humans?
6	How do you expect 3d printing technologies may affect various Industries in the future?
7	How do you expect 3d printing technologies may affect the following aspects of production and consumption in the future: • Production, supply chain and localisation • Business models and competition • Consumer behaviour and market trends • Intellectual property and policies
8	What are the elements that may be missing from 3d printing? Any particular ideas that would make it easier for you to interact with 3d printing technologies and accomplish your goals via 3d printing?
9	What is the role of technology, and 3d printing technology in particular, in makerspaces? What do these technologies mean in terms of the new economy and the society at large? What are the (1) barriers, (2) enablers, (3) opportunities?
10	What is the role of people in makerspaces? What do these people and their skills mean in terms of the new economy and the society at large? What are the (1) barriers, (2) enablers, (3) opportunities?

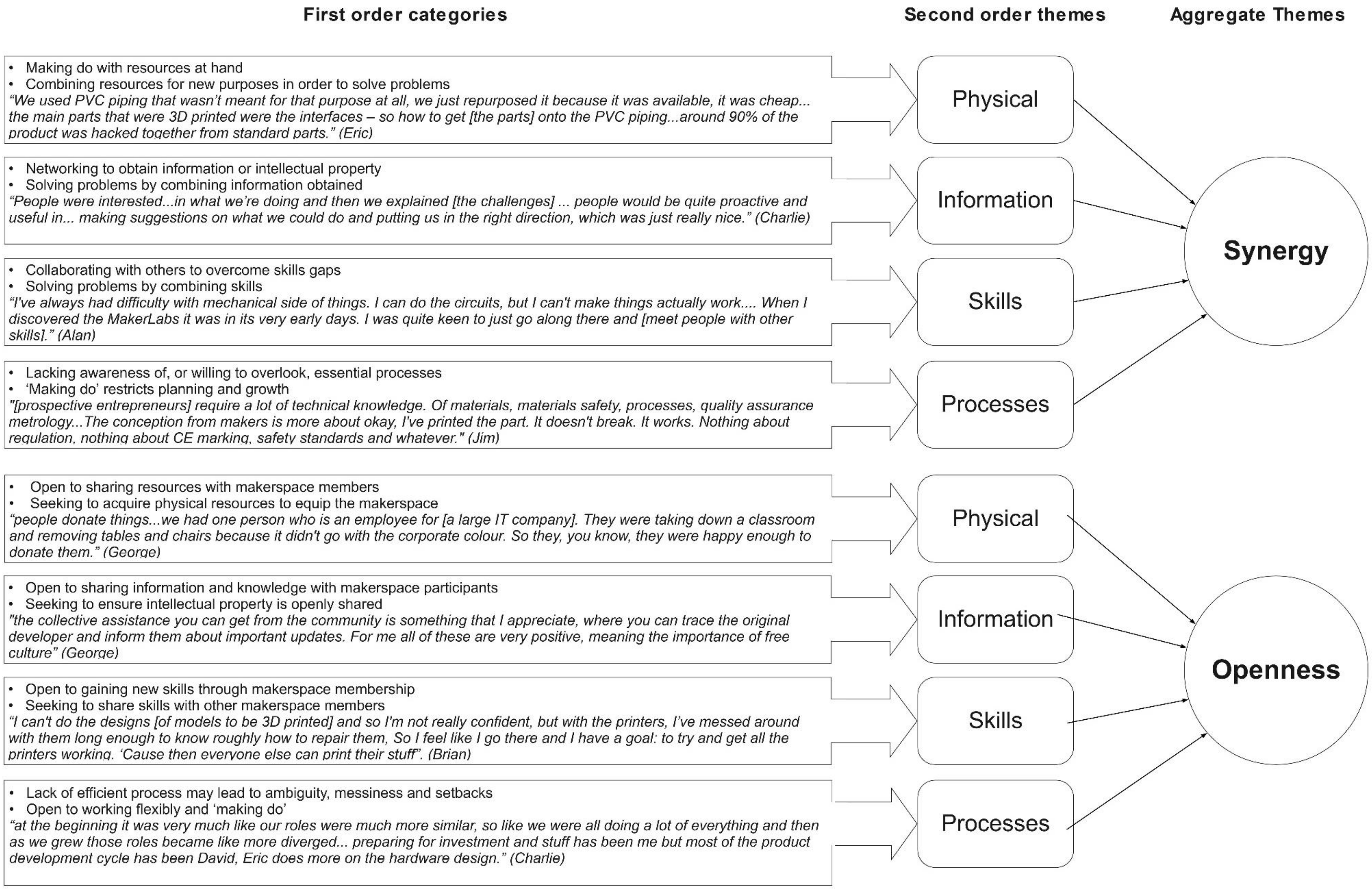

Figure 1 – Data Structure explaining inductively generated dimensions of bricolage

Figure 2 – An example of bricolage: 3D printed parts combined with electronics and other components to create a bicycle gear shift mechanism

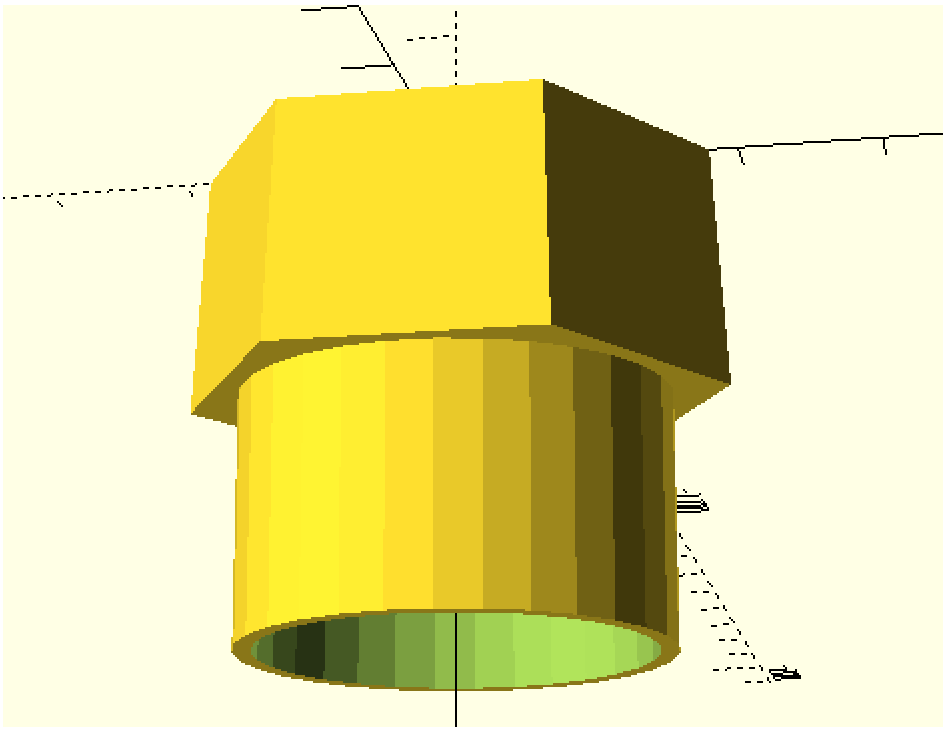

Figure 3 – A radiator handle, designed to be 3D printed by Alan to help a neighbour who suffers from arthiritis

Table 1 **-** Four Makerspaces investigated and list of makerspace members interviewed

Makerspace (pseudonym)	Description	Summary of interviewed makerspace participants (pseudonyms)
MakersLabs	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.	Alan – Retired engineer, developing and helping others develop products, for home use or curiosity, early adopter and user of 3DP. Brian – Software developer, seeking to develop knowledge and experience with future commercial projects in mind.
MakerStart	Subscription based makerspace/incubator, supporting startups and social enterprises. Attracts mainly young graduates and entrepreneurs, particularly those with art and design related education.	Charlie – graduate of natural science and co-founder of company developing agricultural environment monitoring device David – graduate of natural science and co-founder of company developing agricultural environment monitoring device Eric – graduate of design and innovation, joined Charlie and David's company to support product development Frank – engineering graduate, developing a number of independent projects for possible commercialisation
Innov8	Subscription based makerspace, mainly used by professionals developing hardware	George – Scientist and engineer, working on several commercial projects. Experienced CAD and 3DP user, has helped start makerspaces. Harry – Former visual effects worker, now in an office job. Interested in learning 3DP to support desired return to a more creative career.

UniLab	University model workshop, unofficially made available to students for independent project.	Ian – Recent graduate who used 3DP in a student project, developing an automatic bicycle gear shift mechanism for potential commercialisation. Jim – Engineer, with experience in a number of makerspaces and supporting makerspace members to commercialise products