Open at birth? Why new firms do (or don't) use open innovation

Anne Greul, TU München
Anne.Greul@gmx.net

Joel West, Keck Graduate Institute
kgi@JoelWest.org

Simon Bock, TU München
info.simonbock@googlemail.com

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Abstract

Research Summary (92/125 words)

Open innovation is about firms harnessing knowledge flows across firm boundaries, but limited research has examined the nature and antecedents of these flows for startup firms, as well as the interdependence of inbound and outbound flows. From a new sample of startup firms making 3D printers, we show how their degree of openness for inbound and outbound knowledge flows relates to the firms' initial capabilities and founding intentions. From this, we suggest that the patterns of openness are influenced more by initial factor endowments than a firm-specific process of emergent strategy development.

Managerial Summary (122/125 words)

Innovative firms often face tradeoffs between open and proprietary strategies, particularly in industries and segments where online communities and other collaborations provide a pool of shared knowledge for the entire industry. This study illuminates these tradeoffs by comparing the choices made by the founders of 3D printer manufacturers. For products based on modular systems, it shows the range of choices that firms have on their degree of inbound openness (using external technology) and outbound openness (sharing their own technology) — as well as the interdependencies of these choices. Finally, it points to long-term implications of early entrepreneurial decisions: firms that leverage external technology can enter a market more quickly, but their innovation options will be limited unless they have capabilities for proprietary innovation.

Keywords: knowledge, modularity, selective revealing, competitive advantage, human capital

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1. Introduction

Open innovation allows firms to profit from innovation when they lack the end-to-end vertically integrated capabilities to create and commercialize innovations. By partnering with external organizations, firms can harness inbound or outbound knowledge flows to fill gaps in internal capabilities (Chesbrough, 2006; Lee et al., 2010). However, openness carries with it certain risks and other costs (Enkel et al., 2009; Dahlander & Gann, 2010).

Managers who embrace openness face the practical question of how open is open (or closed) enough — including when, how and how much to open, so they can satisfy the goals of both external partners and the ability of the firm to capture proprietary returns (West, 2003; West & O'Mahony, 2008; Balka et al., 2014). An important potential partner for open innovation strategies is an innovation community (Dahlander et al., 2008; West & Lakhani, 2008), which can provide external knowledge flows that enable entrepreneurial entry (Gruber & Henkel, 2006; Dahlander, 2007). At the same time, when working with communities, firms must decide whether to allow outbound flows of knowledge that might aid rivals (Henkel, 2006; Alexy et al., 2013).

Despite the recent popularity of open innovation research (Chesbrough & Bogers, 2014), there remain important gaps. First, there has been almost no research on how open innovation is practiced by new or young firms (Brunswicker & van de Vrande, 2014; West & Kuk, 2016). Secondly, open innovation research has emphasized the use of inbound knowledge flows rather than how firms simultaneously consider both inbound and outbound flows (Burcharth, Knudsen & Søndergaard, 2014; West & Bogers, 2014).

In this study, we ask two related questions: how do new firms utilize both inbound and outbound open innovation — both in terms of degree and mechanism – and why they make such choices. We ask these questions in the context of the new industry of consumer 3D printers, products that integrate computer hardware and software into an IT system. Our study draws on a new dataset of 144 3D printing startups, combining archival data and interviews with founder-managers of young firms. We use that data to develop a series of propositions and a conceptual model linking firm capabilities, IP strategies and founder intentions (as defined by Shah & Tripsas, 2007) to a firm's choice of inbound and outbound openness.

Our sample offers new insights into the Mintzberg (1978) conception of emergent strategy. Most of the firms were similar in using an emergent approach for identifying market niches and building products to serve those niches. However, they realized different trajectories that appeared influenced by two crucial pre-founding differences: the strength of the technical human capital of their founders, and the motivations of the founders for launching their firm. Our study suggests that most of the firms launched based on inbound innovation are fundamentally different from other firms, but that such inbound openness is an imperfect substitute for firm capabilities. From this, we identify opportunities for future research on entrepreneurship and open innovation.

2. Theoretical Background

Open innovation is defined as the intentional management of inbound and outbound flows of knowledge for firms to advance their innovation strategies, by which firms leverage external partners both as sources of innovation and paths for commercializing their own innovations. These knowledge flows may or may not require a monetary payment such as a royalty (Chesbrough, 2003, 2006; Dahlander & Gann, 2010; Bogers & West, 2012).

However, one major gap in open innovation research is understanding its use by *small and new firms.* The evidence for open innovation was originally developed based on studies of large multinational firms such as IBM, Intel and Procter & Gamble that have a long history of success in creating and commercializing innovation (Chesbrough, 2003, 2006). Only more recently have scholars examined the use of open innovation practices in smaller firms (van de Vrande et al, 2009; Brunswicker & van de Vrande, 2014). Because they lack complementary assets, such firms often need external commercialization partners, but face ongoing challenges winning these partners (Teece 1986; Vanhaverbeke & Cloodt, 2006). Although the propensity for open innovation increases with firm size, even medium-sized firms rarely seek to leverage outbound flows (Brunswicker & van de Vrande, 2014).

Open innovation research on smaller firms has emphasized small rather than new firms: of 19 SME-related open innovation studies reviewed by Brunswicker and van de Vrande (2014), most focused on small or medium-sized firms or a comparison of small and large firms, with only two considering the open innovation strategies of new firms. In many ways, the challenges of small and new firms are similar: the liabilities of smallness and newness include a lack of legitimacy, and with it, increased difficulty obtaining internal capabilities, external partners and achieving long-term survival (Aldrich & Auster, 1986; Gruber & Henkel, 2006).

However, brand new firms also face unique challenges that include the absence of trained employees, internal processes, customers and revenues (Aldrich & Yang, 2012). While some of these risks are mitigated by a successful launch, research suggests that many of the liabilities of newness continue on for several years. Based on a review of prior research, Aldrich & Auster (1986) concluded that firms less than 5 years old and less than 20 employees faced the highest failure rates. Henderson (1999) found that among PC manufacturers that selected the winning technology, the liabilities of newness peaked after 4-5 years.

The appropriate use of external sources of innovation has been shown to improve firm performance (Laursen & Salter, 2006). Meanwhile, the liabilities of newness are particularly high for innovative technology-based startups (Efring & Hulsink, 2003). Several previous studies sought to demonstrate how the particular source of external innovations — open source software communities — improved the success of startup firms. Gruber & Henkel (2006) concluded that this knowledge reduced entry barriers and the liabilities of newness and smallness, while Dahlander (2007) showed how firms leveraged community knowledge to develop new business models. Despite these benefits, the availability of the same open source software to rivals also commoditizes competition and thus reduces the opportunity for differentiation (West & Gallagher, 2006).

New firms must thus consider the risks and rewards of openness. Inbound acquisition of proven external technology could reduce a firm's risk of product failures and speed time to market, while at the same time linking it to commodity technology available to competitors. Meanwhile, outbound flows of a firm's own knowledge can strengthen its ties to external customers, complementors and communities, while exposing that knowledge to current and future competitors (Gruber & Henkel, 2006; West, 2003; West & Gallagher, 2006).

A second open innovation research gap is studying the *simultaneous use of inbound and outbound knowledge flows.* Most studies consider one or the other but not both (West & Bogers, 2014). While Enkel et al (2009) have referred to such combined flows as "coupled" open innovation, in many cases the existence of such collaborations has been assumed to prove a combination of flows, without regards to the nature, degree or even existence of these flows.

One potential partner for such collaborations is an innovation community, which here we define as a distributed group of virtually-connected individuals united by a common goal or purpose (West & Lakhani, 2008). These communities can provide a potential source of knowledge inflows (Dahlander et al., 2008; West & Lakhani, 2008; Boudreau & Lakhani, 2009). Knowledge collectively generated, organized and held by a community can be an important input to a firm's innovation efforts (Wang & Ramiller, 2009). While some communities preferentially help a single firm, many provide knowledge flows for a wide range of competing firms (West & O'Mahony, 2008). Open innovation research has assumed that firm collaborations with such communities fit the coupled model of bidirectional flows (e.g., Piller & West, 2014), but these flows have typically not been measured.

Overall, there are a handful of studies that have examined the simultaneous choice of firms for both inbound and outbound flows. Surveying 331 small and medium-sized Danish firms, Burcharth and colleagues (2014) concluded biases against inbound and outbound open innovation reduced the use of these practices. Based on a survey of 681 larger Belgian manufacturers, Cassiman and Valentini (2016) found lower R&D productivity for firms that practiced both inbound and outbound open innovation, but their data could not explain how or why the firms chose these practices.

Therefore, in this study we ask two questions. The first is: how do new firms utilize inbound *and* outbound openness — both in terms of degree (cf. West, 2003) and also the nature of openness? The second is why do firms choose such inbound or outbound knowledge strategies? We are especially interested in the two most anomalous choices, of *not* using free inbound flows of knowledge from a community and allowing free revealing to such communities (cf. Dahlander & Gann, 2010).

3. Methods

3.1. Research Context

To understand how new firms use inbound and outbound openness strategies we sought a sample of firms where there was a high rate of entrepreneurial entry by similarly situated firms, and a clearly identifiable pool of openly available community knowledge that all of these firms might draw upon or contribute to. Because industry context plays a crucial role in determining the basis of competition and nature of competitive advantage (Dess et al., 1990), and because replication is an essential part of a multi-case design (Eisenhardt & Graebner, 2007) we sought a sample within a single industry to control for such differences and allow us to better contrast the impacts of differences between firms in their openness decisions. When a radical technological change brings the emergence of a new product class, this brings a period of rapid entry by new firms and incremental technological improvement (Tushman & Anderson, 1986). Thus, the beginning of such a period (particularly when there is little participation by incumbents) provides an opportunity to study similarly-situated new firms and their innovation strategies.

Here we study the emergence of consumer 3D printers. The first 3D printers in the 1980s were priced at $100,000+ and targeted industrial niche markets. The consumer market was created after 2005 through two changes that diffused crucial technical knowledge. The first was the imminent expiration of the key patent that protected the low-cost Fused Deposition Modeling technology; the second was the creation of RepRap, an online innovation community for developing and disseminating an open source 3D printer design based on this technology. Together, this brought explosive growth in the entry of new firms and new products (de Bruijn, 2010; West & Kuk, 2016).

As the context, 3D printing also provides an important opportunity to contrast the established literature on firm strategies using open source software. As with open source software, the RepRap community provides knowledge flows that reduce both entry and imitation barriers for new firms. In fact, many aspects of knowledge sharing policies and infrastructure in RepRap were explicitly modeled after open source software (de Bruijn, 2010). At the same time, there are important differences: the need to produce tangible products requires differences in both a firm's business model and the relationship of a firm to the community (Balka et al., 2010).

3.2. Data Sources

As recommended for qualitative research, we assembled our data from a variety of sources (Eisenhardt & Graebner, 2007; Yin, 2013). Much as Dahlander (2007) did for open source software companies, we built a proprietary database of firms formed to commercialize technology from the open community. Potential companies were identified through multiple channels, including 3D printing and hobbyist publications, websites, reviews and listings, 3D printing fairs, and Internet searches. To extend this list, we showed the list to some of our interview subjects and asked them to suggest other companies. Data on these firms came from these sources, as well as two databases on new tech firms (Crunchbase, AngelList[1]), websites that sponsor or track entrepreneurial crowdfunding, third party sites that enable open design sharing (specifically Grabcat.com, Github.com, RepRap.org, and Thingiverse.org), the respective company websites, earlier versions of a company's website saved at the Internet Archive (Archive.org), and from interviews.

We included firms if they met four criteria. First, the company must develop and manufacture at least one 3D printer of its own design; when ambiguous, we excluded products that used the same name, i.e. reselling the design of another manufacturer or an open source community. Second, we looked for companies that either shipped products, or had a working prototype and plans to sell actual products within 12 months. Third, to focus on the growing consumer market, the retail price of at least one of the company's printers had to be below $10,000. Finally, to fit our research questions we limited our sample to new or small firms. Most of these firms in our sample were startup firms, but we also included spinoff firms and those existing small businesses that were relaunched to focus on this new opportunity. However, we excluded two older and larger incumbent industrial 3D printer firms that entered the consumer market: 3D Systems (founded 1986) which announced its own consumer printer in 2012, and Stratasys (founded in 1989) which in 2013 acquired the largest startup firm, MakerBot (West & Kuk, 2016).

1 Because of their small size, private ownership and geographic diversity, we could not obtain information on these firms by conventional databases of firms such as Hoover's or the SEC's Edgar. Instead, we utilized Crunchbase and AngelList, two online directories of technology startups compiled through crowdsourced user-contributed content. Because of their unknown reliability, wherever possible we sought to confirm this data using other sources.

For each company, we noted (when available) its name, website, founders, current products, printing technology, price points, and previous crowdfunding efforts. The printing technology was not a sampling criterion, but the price constraint meant that printers used one of three low-cost technologies: Fused Deposition Modeling (FDM) that melts plastic filament; stereolithography (SLA) that uses a laser to fuse liquid plastic resin; or digital light processing (DLP), a variant of SLA that uses an optical semiconductor chip instead of a laser.

In the end, we identified 144 companies across 25 countries. Of these, 138 were based in North America, Europe or Asia (Table 1). None of these companies were public: as of April 2017, no consumer 3D printing company had yet filed for (or completed) an IPO[2]. However, two firms were acquired by larger firms: MakerBot (acquired in 2013) and Robo 3D (acquired in late 2015). While the database likely has omissions, we believe it to be the most complete research database thus far of firms making consumer-oriented 3D printers.

To ensure insights into each firm's openness strategy over its lifetime, we sought an interview with one of its founders. Of the 144 companies, we identified e-mail addresses for 81 of the firms, and from May-December 2014 contacted these firms via e-mail or (in a few cases) in person at trade shows. We contacted 75% of the North American firms and interviewed 29%; we believe our results are generally representative of these firms. We also contacted 58% of the European firms, interviewing 16%.[3] Our sample included the largest European firm (Ultimaker) but not the largest

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[2] Of 11 major industrial 3D printer makers identified by West and Kuk (2016) founded from 1985-1997, six completed an IPO after an average of 10 years, three were acquired by one of the two largest companies, two failed (including one of the public companies) and one remained private.

[3] Among European countries, our response rate varied from 0% for France, Poland, Portugal and Spain to 67% for Germany, with the UK, Italy and Netherlands in between; our German response rate was undoubtedly improved by a German university affiliation for our team. One of the few variables we could compile for all firms in the database was their crowdfunding status. In North America, 38% of the firms that attempted crowdfunding agreed to an interview, while the response rate was 13% for those that did not; in Europe, the comparable numbers were 17% and 16%.

US firm (MakerBot)[4]. In the end, we were able to interview representatives of 28 of the 144 companies (a 19% response rate) — in nearly all cases, the CEO or another founder of the firm who remained active in the company. Most shipped their first product within a year of their founding (Table 2).

These were young and small companies. Of the 28, 25 were *de novo* startups[5] and 20 of these 25 were founded in 2012 or later and thus were less than three years old at the time of our interview; overall, 89% were founded in the four years prior to our data collection. Although we did not explicitly capture firm size, it was clear from the interviews that nearly all had less than 10 employees, and most had only 1 or 2 employees beyond the founders.

These interviews were conducted in person, via videoconference or telephone; they ranged from 25 to 73 minutes, averaging 45 minutes each. We supplemented these company interviews with interviews with two industry experts: the founder of *Make* magazine — the leading consumer magazine for 3D printer buyers — and a manager at a publicly traded 3D printing service bureau that serves both commercial and consumer buyers. Each interview was recorded and transcribed. Firm and product information from the database was used to prepare for the interviews, and also to help interpret and contrast the interview results. This triangulation improved the accuracy and completeness of our conclusions (cf. Eisenhardt, 1989; Yin, 2013).

The interviews followed a semi-structured protocol, which was updated based on what was learned during the interview process. The protocol focused on three topics: (1) the process and stages that the user entrepreneurs pass through when starting their company and developing

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4 MakerBot was the market leader with 38% global market share in the year it was acquired. We tried repeatedly to obtain an interview with two of the founders (the third could not be located) but received no response.

5 The other three firms were either a small firm parent firm spinoff (with common ownership) or a diversifying entry. While these two strategies began differently, over time the results of these strategies appeared similar to each other — each largely similar to a *de novo* startup by a serial entrepreneur.

products, from their founding motivations up to the current point in time; (2) their engagement in open source software and hardware projects; (3) the company's choice of the nature and degree of openness. The interview protocol is listed in Appendix 1.

3.3. Data Analysis

Grounded theory was used to derive theoretical insights from the interview data (Corbin & Strauss, 2008). We used this to understand how our founders made sense of the central questions of our study (cf. Suddaby, 2006) — in this case, the meaning, antecedents and consequences of their firm's openness decisions. As recommended by best practice (Eisenhardt & Graebner, 2007; Eisenhardt et al., 2016), we refined our understanding of the data through iterative processes of analysis and interpretation.

NVivo software was used to perform a three-step analysis (Hutchison et al., 2010). First, an extensive coding scheme for organizing and structuring data was developed based on thematic coding of initial key interviews and concepts derived from the research question. This coding scheme was used to code the remaining majority of interviews in a structured way, while still allowing the creation of new codes along the way. Second, to analyze patterns and dominant themes, codes were analyzed within NVivo based on similarities and cross case patterns. Finally, these patterns were used to identify potential constructs. NVivo Nodes "search queries" was used to verify initial assumptions about patterns found while conducting the interviews, as well as organizing findings to be retrieved for the analysis and writing process.

The authors met virtually to discuss preliminary interview findings and identify potential relationships between these constructs. From this, we developed a series of classification metrics for various attributes of these firms' openness and entrepreneurial strategies, and used these metrics for coding each firm based on the interview data or (when those data were ambiguous or incomplete) our archival data sources. Because our goal was inductive theory-building, we compared our emergent theoretical constructs and relationships with prior research, both to refine them and generate theoretically relevant insights (cf. Eisenhardt et al., 2016). Table 3 summarizes our categories coded for each firm that we talked to.

4. Entrepreneurs, Openness and Founding Strategies

Although our entrepreneurs were bringing their products to market in the same industry during a narrow four-year window, they differed considerably in their backgrounds, goals and strategies. To measure their open innovation strategies, we specifically examined their choices for inbound and outbound knowledge flows, and discuss below how our data revealed multiple levels of inbound and outbound openness within our sample.

An inductive analysis of our data suggested three important differences between these firms that seemed related to openness: two related to the founding strategy, and one a direct consequence of that strategy. The first founding strategy was building upon the founders' technical capabilities that enable proprietary innovation (cf. Helfat & Lieberman, 2002). The second was the firm's pursuit of formal IP protection (i.e. patents), which reflected those capabilities, its success in developing innovation and the founders' attitudes towards patenting those innovations. Third, our interviews unexpectedly identified two different dimensions of a founder's intentions within the Shah and Tripsas (2007) typology: a user entrepreneur (vs. a non-user entrepreneur) and an "accidental" entrepreneur without initial motivation to commercialize his idea (vs. an opportunity-driven one).

We coded these strategic choices, and then looked for relationships between these choices and openness in our data, and possible explanations for these relationships from our founder interviews and secondary data. In some cases, the explanations that entrepreneurs gave for their openness choices suggested linkages between inbound and outbound choices, and so we systematically analyzed our data for patterns (and explanations of patterns) of such linkages.

Below, we use our data (with an eye to prior theory) to present these relationships in terms of formal propositions. Consistent with recommended practice (e.g., Eisenhardt & Graebner, 2007), we summarize these propositions using a model, as shown in Figure 1. Firms with strong technical capabilities are less likely to use inbound and outbound openness, as are firms that have developed strong IP. Within our sample, we found that the intentions of the founders might cause them to be more or less willing to allow outbound openness. Finally, only the firms that make extensive use of inbound flows will allow outbound flows.

4.1. Inbound and Outbound Flows

Most of the research on open source software — and open innovation more generally — has bifurcated between firms that did or did not use inbound (or outbound) knowledge flows. Our field work quickly suggested significant variance in the nature and degree of both inbound and outbound openness used by the firms. Therefore, from our data we developed new measures of the degree of openness for these hardware/software systems: for both inbound and outbound flows, we found examples of full openness, no openness and two forms of partial openness.

Allowing Outbound Knowledge Flows

The most fundamental difference between the firms was their degree of outbound openness. Our interview protocol asked whether firms allowed hardware or software designs to be openly disclosed outside the firm, the restrictions on such disclosures, and for examples that illustrated these policies. To clarify and confirm the respondents' choices, we reviewed secondary data on the company website or third party open design sharing sites. Table 4 shows representative quotes for the outbound openness strategy of each firm.

We coded the firms' openness strategies based on the degree of architectural openness, i.e. how much of the system is open: everything, a part, or none — corresponding to the "opening parts" distinction of West (2003). A second dimension corresponded to his "partly open" distinction: differences in the reuse openness meant whether or not the firm imposed "non-commercial use" restrictions, intended to allow the technology to be used by customers and the innovation community but not by competitors.

The firms in our sample were almost equally distributed in terms of how much was opened, i.e., opening everything, opening parts, and opening nothing. However, one cell was empty: for the firms that opened only part of their technology, all did so with restrictions against commercial reuse. When the fully proprietary case was added to the 2x2, this resulted in five possible approaches to outbound openness, ranging from fully open to fully proprietary (Figure 2).

Everything Open. Firms in this category freely revealed all of their product design sources to the community and the broader public. However, within this category were two distinct approaches. Three firms made hardware designs fully open without restriction, similar to the terms by which they had received the external technology from RepRap and other communities. The other seven firms were concerned about surrendering proprietary advantage that might enable potential competitors, with a "partly open" strategy that attempted[6] to impose restrictions on the use of their outbound knowledge flows.

Open Parts. Nine firms shared parts of their designs while keeping others closed — corresponding to "opening parts" (West, 2003) or "selective revealing"[7] (Henkel, 2006; Alexy et

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6 The RepRap project originally used a software license, but there are problems extending copyright-based software licenses to hardware designs (Ackerman, 2008) and the effectiveness of such license for hardware is an unresolved business and legal issue.

7 Alexy et al. (2013: 272) defines selective revealing as "the voluntary, purposeful, and irrevocable disclosure of specifically selected resources … which the firm could have otherwise kept proprietary."

al., 2013). These parts were open either to allow customers to create added value through customization (Henkel et al., 2014), or to be able to leverage open source designs and therefore inbound knowledge flows. Entrepreneur E said: *"The physical interface between the printer and the extruder will be opened up … so that you can build your own extruder and it will work with ours."*

Interviews showed that firms were very cognizant of the risk of helping potential competitors. Entrepreneur E said he would not open technologies that customers were not skilled enough to modify, because that would "*reduce the R&D costs and the time to market [for] our competitors who are not playing by the same rules."* Among the firms that opened parts, there were also significant differences in terms of what part of the system was open and what was not — with firms emphasizing openness that enabled customer modular experimentation (cf. Henkel et al., 2014).

Nothing Open. Nine firms did not reveal any of their technology or designs outside the firm boundaries, treating them as trade secrets. This proprietary approach tended to limit their ties to the communities and community technology. Respondents gave three reasons why they didn't disclose technology (particularly hardware):

- When no open designs or components were leveraged — particularly when no relevant knowledge was available — the entrepreneur saw no need to reveal designs beyond the boundaries of the firm. Entrepreneur S said: *"I have seen just a few people working on their own DLP 3D printer. ... We had to develop basically from scratch. When we started, there were very [few] references to start with."*
- Some feared their knowledge would be exploited by current or future competitors and that opening up the sources would significantly accelerate this process, as West (2003) saw in open source software. Entrepreneur F said: *"If we would completely open it up,*

we would know that there would be another company by tomorrow, which copied our concept a hundred percent."

- Firms were concerned that promising openness to buyers could provoke a negative reaction if its business strategy changed later on. Aware of the strong criticism of MakerBot's switch from open to closed IP policies (West & Kuk, 2016), Entrepreneur P said: *"one of the reasons that we didn't go open source is largely because of the risk of changing our mind down the road and what a disaster that would have been."*

Utilizing Inbound Knowledge Flows

Inbound open innovation involves bringing knowledge flows into a firm to aid its innovation strategy (Chesbrough, 2006; West & Gallagher, 2006). For entrepreneurs seeking to create consumer 3D printers, the largest pool of knowledge came from the RepRap online community that later provided open designs for more than 50 printers. These hardware designs incorporated three types of components: commodity hardware parts (motors, rails, bearings, belts), open source components from other projects (such as the Arduino and Sanguino circuit boards), and new open source printing components (such as the extruder nozzle) developed by RepRap members. The project also developed open source software that ran on the host computer (such as drivers) or in the printer (firmware), and maintained a directory of external sources of such software (de Bruijn, 2010; West & Kuk, 2016).

Although the RepRap community was widely known, we found a range of approaches of how and how much firms used inbound flows in their designs. This was consistent with the open innovation principle that such flows may be in the form of knowledge, or that knowledge may be incorporated in components or other innovations sourced by the firm (Bogers & West, 2012). We found three categories and four levels of reusing community knowledge:

- adapting a complete system design that was incrementally improved by the entrepreneur to quickly bring a product to market;
- two levels of reusing specific components in designing a firm's own products, and
- studying the designs for learning, without reusing components or system design.

These reuse categories were cumulative, in the sense that systems reuse included component reuse, and system or component reuse included knowledge reuse (i.e. learning). Table 5 shows representative quotes for the inbound openness strategy of each firm.

System Reuse. Seven firms explicitly came to market with a product derived from one of the RepRap open hardware designs, all using the same (FDM) printing technology. As with startups reselling open source software (Dahlander, 2007), they augmented or customized the existing open system design rather than designing a new system from scratch, reducing the capital and time required to generate initial revenues. Entrepreneur B described how he launched his first product based on the RepRap Mendel design: *"Our first sale was the [product name] kit, which occurred in the month that [our company] was launched."*

Component Reuse. Complex systems are constructed from individual components that can be used in the original design, or reused in the firm's new design (Baldwin & Clark, 2000; Haefliger et al., 2008). For such products, partitioning a product architecture into discrete components with well-defined interfaces allows reuse of those components to reduce development costs and increase component economies of scale (Ulrich, 1995). Such a modular component architecture is particularly important for IT systems, where interfaces allow decoupled innovation and the reuse of standardized components provides enough scale to fund R&D intensive investments (Baldwin & Clark, 2000; Langlois, 2012).

Fifteen firms reused components but not the system, and these 15 firms fell into two groups. Twelve of these reused pieces of the open hardware design — the mirror image of opening parts — to speed their designs to market; these firms included all degrees of outbound openness: fully open, partially open or fully closed. Three firms only reused software. Overall, 21 of the 28 firms in our sample used one or more of the open source software packages developed to support the RepRap hardware — either as a software component or as part of reusing the entire system[8].

All three of the firms using SLA printing technology reused software components from RepRap. Lacking an open design, these firms had the most difficult hardware R&D challenges, but the SLA technology also provided improved print quality over the FDM-based open hardware designs. The three firms did not feel the need (or perhaps have the resources) to develop proprietary software. Entrepreneur N was proud of his proprietary hardware but more open in his use of software: *"we use a lot of open source software and we've contributed back to a few projects."*

Learning. As with software (Lerner & Tirole, 2002), the availability of an open design allowed engineers to train themselves in system design.[9] All of our entrepreneurs used some form of community knowledge, but six firms limited their use of inbound knowledge flows *only* to learning rather than reuse of a technical component or system design.

In the interviews, even the most proprietary entrepreneurs noted that the RepRap open implementation had played an important (often crucial) role in how they learned about 3D printers. This included how to use and assemble a printer, various tradeoffs in the overall system design, technical approaches to specific aspects of the product design, and the limitations of current

8 Every 3D printer requires two crucial drivers installed on the host computer: one to convert 3D application drawings into 2-dimensional layers, and another to convert these layer definitions into standard print codes. Some printers also utilized printer-based open source firmware, but the use of such software was more difficult to independently verify.

9 Originally written by a college student, the open source Linux was modeled after the Minix operating system developed by a college professor for teaching operating system design (Wayner, 2000).

products. Entrepreneur F said *"my co-founder experienced a lot of problems when working with these 3D printers. ... [That] is why we developed the [product name]."* Entrepreneur M said: *"The open source helped me self-teach myself what I needed to know about the machine."* For the proprietary firms, such use tended to be limited to the pre-launch period, as the firm sought to move beyond the shared technology available to existing and potential competitors. Entrepreneur P said: *"We evaluated and then concluded that it is not the most cost effective long term solution and that is basically where we stopped."*

4.2. Effect of Technical Capabilities on Knowledge Flows

In general, for firms seeking to differentiate via proprietary innovation, a key challenge is how to obtain the capabilities to create such innovations. For a brand new firm, its capabilities are those of its founders (Helfat & Lieberman, 2002). For young firms, proprietary innovations come from the technical human capital of the firm's founders and employees (Colombo & Grilli, 2005; Sauermann, 2015). When founders have strong human capital, their respective new firms are able to deliver more radical innovations (Marvel & Lumpkin, 2007).

The firms in our sample were young and most were working on their first or second product. Racing to market in a crowded and rapidly growing industry, their product development cycles were weeks or months, not years. At the same time, from interviews and their online biographies, we saw differences in their respective technical expertise, and thus the differentiation of the products that their firms could quickly develop. In our data, the human capital ranged from PhD engineers to ordinary 3D printing users; we categorized the founders' human capital as high, medium or low (Table 6).

We coded those entrepreneurs without a technical degree as having low expertise. Four firms were generally limited to experience using 3D printers, or assembling them from a kit. For example, Entrepreneur D said *"I'm a music major by training, I'm a violinist. I have no formal background in engineering, but I've got a ton of informal background"*.

We identified 11 firms with founder(s) as having high technical capabilities, when they had a formal degree or significant practical experience relevant to the field of 3D printing (e.g., PhD in mechanical engineering or robotics). For example, Entrepreneur H said *"We had been working together for a number of years, we were in the field of automation, then we got involved in CNC and then laser cutting, and then finally 3D printing about 15 years ago."*

We coded 13 firms as having a medium level of expertise, when they had appropriate education or experience in an adjacent field, such as software engineering or operating high-precision computer numerical controlled machines that were the antecedents to 3D printers (cf. Gibson et al., 2010). For example, Entrepreneur W said that his co-founder "*hasn't done any 3D printing but he's done all kinds of other stuff, you know, a little bit of programming, a little bit of hardware hacking, various metal working, just a hobby sort of maker's stuff we all do"*.

The level of human capital appeared to drive the firm's open innovation strategies. Founders with low levels of technical capabilities were almost entirely dependent on (non-differentiated) open community technology for bringing products to market: accordingly, all had very high levels of inbound flows. For example, Entrepreneur M said his first product "*is pretty much like the Prusa Mendel and a hand full of other designs."* As predicted by West & Bogers (2014), inbound flows substituted for internal capabilities, as when Entrepreneur D said *"We did join the community and find help, and we got help at the early stages."* However, this knowledge proved only a limited substitute as the firm eventually outgrew the community's knowledge.

Meanwhile, founders with high level of such technical capabilities were less likely to use external technology, and more likely to develop their own technology: only one of the 11 had the highest level of inbound flows, and four had the lowest. Entrepreneur F cofounded his firm with a robotics Ph.D. student, and as a result found no value in inflows of community knowledge. Similarly, the founders of Firms Q and Z had mechanical engineering degrees from top engineering schools, and made limited use of external technology. Thus, we predict

> *Proposition 1: The more technical capabilities a startup firm has, the less inbound knowledge flows it will use from an open community.*

In terms of outbound flows, founders with lower levels of technical capabilities lacked the ability to create proprietary technologies and were more tied to the community, and thus more likely to share their incremental modifications. As Entrepreneur M said: "If we use open source stuff, we should give back to it. When we come up with something new, we try to post it and share it with people so that it is out there." These firms also leveraged this sharing and visibility to generate goodwill with the community, gaining marketing and other benefits from these ties.

Firm with high levels of technical capabilities were less open in sharing: eight of the 11 were fully proprietary. Not only did they fear enabling rivals, but also the distraction of supporting the technology; as Entrepreneur C explained why he didn't share: "too many people will call us expecting us to support it as an open source and we can't do that. We don't have the time to do that." Meanwhile, the entrepreneurs with medium level of expertise adopted intermediate positions on utilizing external technology and sharing their own technology. Therefore, we predict:

> *Proposition 2: The more technical capabilities a startup firm has, the less unmonetized outbound knowledge flows it will allow.*

4.3. Role of Proprietary IP

Proprietary IP is valuable to firms because it allows firms to create competitive barriers and raise outside investment (Graham et al., 2009; Hoenig & Henkel, 2015). While high levels of technical capabilities were common among our entrepreneurs, strong proprietary IP was less so. In our data, the effect of technical capabilities upon openness was partially (but not fully) mediated by the decision of a firm to file for proprietary IP.

The products and interviews made clear that trade secrets would have little effect on protecting a firm's hardware designs, because the act of selling the printer was the act of disclosing the design choices (cf. Teece, 1998). We thus chose to measure proprietary IP using utility patent filings for two reasons. First, such a patent is the strongest form of IP and thus the IP most valued by investors. Secondly, the cost of patents represents a sizable financial investment for an early stage company.

We used patent applications, which for very young companies have been shown to provide a predictive power parallel to that of issued patents for more established firms (Hsu & Ziedonis, 2007). Because our interviews took place in 2014, we looked for utility patents filed or with a priority date (e.g. via a provisional patent) of 2014 or earlier. Under the U.S. and European system, patent applications are published within 18 months, and so April 2017 we would be able to see any patents that filed on or before October 2015. We found three firms (J,N,P) that had an issued patent, and also seven that had published patent applications (Table 3).

When it comes to the relationship of IP choices to a young firm's openness strategies, there are two competing predictions.[10] The first is that because patents provide a strong (albeit temporary) monopoly, firms that file patents will be more open with their technology (Mazzoleni & Nelson, 1998); for example, the pharmaceutical industry relies heavily on patents which allows industry scientists to actively publish their findings (Gambardella, 1992). Conversely, it is possible that the most open firms will be those that do not utilize proprietary IP, due to ideology or other founders' beliefs that are manifest in their strategy (von Hippel, 2005). As one interviewee said, "it does look unseemly to patent things that had been widely available."

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[10] We wish to thank an anonymous reviewer for pointing out these two possibilities.

Our data support the latter prediction, that firms using formal IP had less knowledge flows. Of the 10 firms with a patent or application, 40% of them used the lowest level of inbound flows (vs. 11% for those that don't use patents); 10% had full systems reuse (vs. 33% of those without formal IP). Entrepreneur P said: "I honestly see my product fitting into a different a category than the open source printers. Those printers are great products for the enthusiast and hobbyist market. … [My customers] don't want to do that – they want to buy a product and plug it in and have it work."

Similarly, those firms utilizing patents were also less interested in sharing their knowledge with the community: all but one of the proprietary firms used patents, and all but two of the firms using patents were proprietary. For example, Entrepreneur F said: *"If we would completely open it up, we would know that there would be another company by tomorrow, which copied our concept a hundred percent."* When asked if he would release any hardware designs to the public, Entrepreneur R said *"I don't think we plan to do so."*

The two remaining firms — one with a patent (J) and one with an application (G) —pursued a strategy of opening parts (intermediate openness), with some part of their technology proprietary and other parts not; for example, Firm J developed a proprietary extruder that worked reliably with a wide range of materials. Both firms were willing to open the non-proprietary aspects of their system design, because they hoped that the strong IP on key elements would provide ongoing advantage. Firm J reused hardware elements while G reused an entire system.

The firms without a patent were more open towards leveraging inbound and outbound flows. As Entrepreneur E said, "I am not a huge proponent of patents. …We are not going to try to lock this down." These firms thus adopted strategies that reflected the sort of "free innovation" beliefs represented by copyleft software licenses and free software (von Hippel, 2017). Overall, we predict:

Proposition 3: The more proprietary IP a startup firm has, the less inbound knowledge flows it will use from an open community.

Proposition 4: The more proprietary IP a startup firm has, the less unmonetized outbound knowledge flows it will allow.

Because IP and capabilities are strongly correlated, Propositions 3 and 4 make predictions similar to Propositions 1 and 2. In the three cases (11%) where they are not correlated, one was consistent with P1 and P4, one with P2 and P3, and one with P3 and P4 — suggesting (within the limits of our sample size) that these are separate constructs.

4.4. Founder Intentions

The classical model of entrepreneurship is one where a profit-seeking, risk-taking nascent entrepreneur seeks out an opportunity to create a new venture (Shane & Venkatraman, 2000; Dyer et al., 2008). However, in their pioneering study, Shah and Tripsas (2007: 124) define a different model of user entrepreneurs as "distinct from other types of entrepreneurs in that they have personal experience with a product or service and derive benefit through use." They also refer to accidental entrepreneurs as those "who happen upon an idea through their own use" (S&T: 126). While user and accidental entrepreneurship are related, in our data we found that some user entrepreneurs are more intentional than others in how they found a company. We used the interview and other data to classify all 28 firms on these two dimensions of founder intentions; representative quotations are shown in Table 7. Because outbound flows were scarcer than inbound flows, we analyzed the relationship of each firm's outbound openness to these two dimensions.

Following the terminology of S&T, we operationalized *user entrepreneurs* as founders who were users of 3D printers before they realized a business opportunity and founded their company — and then either improved their printer based on an own need or developed a new printer following their own requirements and ideas. We identified 16 firms whose founders had already developed a prototype before they decided to turn their hobby into a full-time job. For example, Entrepreneur J said *"I was hired as a 3D printing expert with experience with Makerbots. So I worked on that and I made enough money. Then I decided to build the prototype of my own design of a 3D printer."*

Conversely, following S&T we defined *classic entrepreneurs* as those founders that had not been heavily involved in 3D printing before. While some of them had experience with 3D printing, these entrepreneurs selected the industry as a business opportunity before working on a printer design. For example, Entrepreneur G was a business student who said *"I decided I wanted to start a 3D printing company"*, and then developed a design after that.

Prior research makes conflicting predictions about whether user entrepreneurs are more open to sharing than other managers. Some have emphasized the community ties that prompt user entrepreneurs to both access and share information with a community (von Hippel, 2005, 2017; Shah & Tripsas, 2007). Others emphasize the variance among user entrepreneurs, with some being more oriented towards private gain and others towards community benefit (Hienerth 2006; Fauchart & Gruber, 2011).

Our findings are more consistent with the former: in our sample, the user entrepreneurs appeared to be more open than the other types of entrepreneurs. For example, all of the fully open firms and all but one of the partly open firms had user entrepreneurs. The founders of Firm AB started out as user entrepreneurs: "*We first started the company because we wanted to build our own 3D printer after playing with other commercially available printers that we had. And we thought, we could … do a better job."* In regards to their openness strategy the founders explain: *"We published the source code parts which is a variation of open source code. We published some parts designed to help people modify the printer…"*. Overall, we found that user entrepreneurs published at least parts of their designs to support and contribute back to the community.

Conversely only two of the nine proprietary firms were founded by user entrepreneurs. Therefore, we predict:

> *Proposition 5: User entrepreneurs are more likely than classic entrepreneurs to allow unmonetized outbound knowledge flows.*

In our sample, we also found examples of what S&T termed an *accidental entrepreneur.* These entrepreneurs were interested in printers, but did not consider starting a business until they had requests from friends or acquaintances to buy the product— as when Entrepreneur V said *"We founded the company after we had too many people asking to buy a kit. We thought: Why not make this our day jobs and work on 3D printing full time?"*

Conversely, we classified as *purposeful entrepreneurs* those that set out to create a firm prior to determining demand, as when Entrepreneur D described the decision of his founding team: *"When we got it together, we [concluded that] this is an idea worth pursuing."* Consistent with the S&T definitions, among our 16 user entrepreneurs were both accidental (9, 32%) and purposeful (7, 25%) entrepreneurs; however, all of the 12 classic entrepreneurs (43%) were purposeful. Most of the accidental entrepreneurs (88%) ended up at an intermediate level of openness, while only 42% of the purposeful ones did so.

As S&T note, accidental entrepreneurs often leverage community knowledge to develop and refine their product ideas: this may be one reason why most of our accidental entrepreneurs opened technologies that were valuable for the community, but left closed parts that would benefit competitors. Entrepreneur E explained: *"[F]or things that the community can take advantage of, we will open up. For things that the community has no hope of duplicating, we are not going to open it up."* Consistent with S&T, our accidental entrepreneurs also recounted a less systematic pre-launch business evaluation process. This informal launch process, coupled with their age (all but one was two years old or less), suggested that these young firms had spent less time developing their openness strategies and thus chose an intermediate level of openness.

Meanwhile, it appeared that both the proprietary and fully open strategies required more preparation and analysis. The proprietary firms required additional investment and planning to develop differentiating technologies, particularly when patents were involved. Founder Z explained his proprietary approach: "We have a long experience with these products. … We realized that in order to make the best products, you must have a focused engineering team — and a focused engineering team won't keep working for free work."

Conversely, a choice of complete openness eliminated all possibility of technology-based advantage, thus forcing firms to realign all sources of competitive advantage (West, 2003; Balka et al., 2010). Because of the risks of these strategies, they also required more decisive and experienced leadership — consistent with nascent entrepreneurs who purposefully seek an opportunity. One such entrepreneur was (partly open) Founder B, who said: "I felt [the 3D printer] was going to be a game changer for society in general, similar to the impact that the Internet has had on society, so I felt that was something I wanted to jump on the tech curve as early as possible."

Therefore, we predict:

> *Proposition 6: Accidental entrepreneurs are more likely than purposeful entrepreneurs to use intermediate levels of unmonetized outbound knowledge flows.*

4.5. Linkage of Inbound and Outbound Flows

Predictions in prior open innovation research have been mixed about any linkage between the use of inbound and outbound flows. On the one hand, certain modes of collaboration inherently require both flows — as captured by the idea of "coupled" open innovation through such collaborations as strategic alliances (Enkel et al., 2009) or co-creation (Piller & West, 2014). However, others have suggested that these can be separate choices, as discussed in the original

Chesbrough (2003, 2006) conception. Burcharth and her colleagues (2014) found two separate predictors for whether firms would utilize inbound or outbound flows, and many scholars have found evidence of one mode without evidence of the other (West & Bogers, 2014).

Our data demonstrated limited correlation between the firm's inbound and outbound openness decisions. To make a conservative test of comparing the inbound and outbound scales, we classified each dimension as three levels (open, partial, closed) instead of four. In this case, we found 53% (15 of 28) agreement between the respective degrees of flows. Of the remainder, 36% (10) took more knowledge than they gave.[11] Only three (11%) were net knowledge donors: one (O) with full outbound openness and reuse of both hardware and software components, and two (S, T) that shared some of their component designs but did not reuse external components. Beyond three donors, three other firms had neither inbound and outbound flows. From our interview and other data, the explanation for the use of inbound and outbound flows by the remaining 22 firms (79%) fit into one of the following three general patterns:

Collaboration Strategies. Some firms release technology to get customer or other external feedback to improve that technology (Piller & West, 2014). In our sample, the clearest explanation for linking outbound and inbound flows came from firms that released designs to get feedback that would improve those designs. For example, Entrepreneur V said that after a customer released an open source design for an improved printer front panel, the company both adapted that design as an add-on for existing customers and incorporated that functionality in later models. Entrepreneur M described getting feedback on his printer's firmware: "Having more people work with the software,

[11] If we did not collapse the middle categories, the free-riding was even more dramatic, with 10 balanced, 15 taking and 3 giving; the Spearman correlation between inbound and outbound flows is 0.649, vs. 0.527 if the middle categories are combined. The difference corresponded to six firms that reused both hardware and software components, while only releasing a portion of their architecture under reuse restrictions.

you really start refining what the general audience wants. Sometimes some really great ideas come out of it."

Our respondents articulated two moderators of collaborative benefits. One was if rivals could modify the designs but not customers. Entrepreneur P explained why he didn't share: *"With our target customer being non-early-adopter consumers and educators, there was little value or need in providing open-source solutions, and we had no expectation of asking our customers to provide technical insights back to us, so a decision to open-source our designs would have only been risk/downside for us."*

The other moderator was a limited pool of external knowledge that could be accessed. Most of the hardware knowledge in the RepRap community was tied to the FDM technology, making collaboration less practical for firms using other technologies. As Entrepreneur R explained, *"SLA technology is much more complicated than FDM, as it involves not just the mechanical and electrical but also optical and chemical matters."* In particular, firms that had hardware patents appeared more likely to have surpassed the level of the community's knowledge.

Compulsion to Reciprocate. Firms that want to use inbound flows from an open community face pressures to allow their own outbound flows. There may be explicit legal requirements, particularly those (intentionally) imposed by copyleft-style open source licenses (Henkel, 2006) — or there may be implicit social or normative pressures, as Stewart and Gosain (2006) observed in open source communities. We only saw evidence of the former, as with Entrepreneur P's reasons for not using inbound flows: "as we aim to keep many of our technologies proprietary, we wouldn't use any open-source designs whose license would require our use of it to also be open-sourced."

Free Riders. Free riding is always a risk when community knowledge is widely available (Lerner & Tirole, 2002). Eleven firms used more inbound flows than they allowed, including six

(H,I,N,Q,R,Z) that were fully proprietary. Entrepreneurs articulated two main reasons for not sharing: transaction costs and enabling rivals. Entrepreneur AB articulated both motives: "*I used basically the whole internet to get the information I needed at that time.… [However] in my opinion when you're spending a lot of time on the forums [sharing info] you're not spending a lot of time developing.*" He also worried about enabling low-cost competitors: *"It's because we've seen a lot of Makerbot clones and we don't want to have two years of development go down the drain because [of a] company somewhere in China paying three dollars a day while we are paying … $75 U.S. a day for an employee."*

Overall, we found that most (but not all) firms used inbound flows, but fewer allowed outbound flows. In almost all cases, only the firms that benefited from inbound flows would *consider* outbound flows (either due to collaboration or reciprocation pressures). Therefore, we hypothesize:

> *Proposition 7: Startup firms are more likely to allow large levels of unmonetized outbound knowledge flows if they also have large levels of inbound flows.*

5. Discussion

This study compared openness decisions among entrepreneurs in an emerging technology-based industry, tying those decisions to the firm's initial capabilities and the founder's entrepreneurial intentions. Here we discuss the implications for future research and practice related to new firms and open innovation.

5.1. The Path Dependence of Entrepreneurial Openness

New firms face myriad difficulties acquiring resources and building routines and capabilities to deliver value (Helfat & Lieberman, 2002). Open innovation offers firms a potential alternative to end-to-end vertical integration (Chesbrough, 2006; Bogers & West, 2012): inbound open innovation can make it easier for firms to enter and offer products to the market (Gruber & Henkel, 2006;

Dahlander, 2007), while outbound open innovation allows new firms to profit from their innovations without needing to build commercialization capabilities (Teece, 1986; Bianchi et al., 2010).

Prior research suggests that entrepreneurs often use an emergent process to develop firm strategies (Mintzberg, 1978; Mintzberg et al., 2005), and that is particularly true for user entrepreneurs (Shah & Tripsas, 2007; Haefliger et al., 2010). We observed this emergent openness strategy process in a *within firm* analysis of our sample of 28 firms—a process that was very similar to that of Shah and Tripsas (2007) and consistent with Henkel's (2006, Henkel et al, 2014) prior research on openness strategies in software. As predicted by Mintzberg, the high uncertainty of a new venture meant that no plan — no matter how well thought out — survived contact with the real world (McGrath & MacMillan, 1995).

However, comparing the strategies *between firms* showed a different pattern. In most cases, it appears that the die was cast by how these firms were initially launched. Firms launched with strong technical capabilities were able to pursue a strategy of proprietary innovation, had less willingness to share technology and less need to use inbound flows of external technology knowledge. This is consistent with prior research showing a firm is more likely to succeed if it enters with the necessary capabilities, particularly if the new firm is imprinted by this initial entry (Helfat & Lieberman, 2002; Beckman et al., 2007).

Firms without such capabilities were limited to tinkering with community technology (available to all competitors) and thus highly dependent on such inbound flows; this pattern seemed typical of user entrepreneurs. Absent strong sales (or funding) success, they lacked the resources to hire expertise and perform significant proprietary R&D (cf. Harrison et al., 2004), potentially limiting these firms to continue as a persistently small business (cf. Gimeno et al., 1997). Thus, while the high capability firms can create their own path, a choice to enter based on inbound flows may lock a firm into a path dependent trajectory (cf. Garud & Karnøe, 2001).[12]

Unless a new firm can attract outside investment, its growth will be limited by internal cash flows (Carpenter & Petersen, 2002). As we saw in our sample, firms with high technical capabilities can produce the proprietary innovation that attracts outside investment (Hsu, 2007; Hoenig & Henkel, 2015). This has changed recently as the rise of crowdfunding has allowed firms to gain capital in lieu of (or before) obtaining traditional venture investment (Mollick, 2014). In our sample 75% of the firms with proprietary strategies and strong human capital had successful crowdfunding campaigns, versus 35% of the remainder of the sample.[13]

Further research is needed to see if these paths continue to diverge over time. In our data, the initial difference of capabilities was as little as four years of engineering education by one founder: under what conditions is this advantage sustained, whether due to differences in leadership, culture or product strategies? Does higher initial founder capital provide dynamic capabilities that allow better adaptation over time (as suggested by Wu, 2007)?

Conversely, under what conditions can low tech firms obtain enough resources to pursue the growth strategies of their high tech rivals? Other than revenue growth and economies of scale, how can such firms pursue sustainable cost advantages?

In addition to founder capabilities, path dependence was also linked to founder intentions. As might be expected (e.g., von Hippel, 2005), the user entrepreneurs were more likely to allow outbound flows than the classic entrepreneurs. These two polar archetypes corresponded in unexpected ways to the accidental vs. purposeful entrepreneurship distinction drawn by Shah and

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[12] As with other forms of openness, there were various shades of gray in between these extremes (cf. West, 2007).

[13] The relatively high rate of crowdfunding success may be due to part to the early entry of the firms in our sample: all but one of the successful firms were founded before 2014, and our separate analysis of crowdfunding suggested declining success rates over time for the industry.

Tripsas (2007). All of the three open entrepreneurs were purposeful, as were 89% of the nine proprietary entrepreneurs — but only half of the 16 entrepreneurs at intermediate levels of openness. This suggests that the purposeful entrepreneurs have a clearer conception of their openness strategy while the accidental entrepreneurs choose some intermediate position.

Our data imply that accidental entrepreneurs leveraging open community flows are more intrinsically motivated, while purposeful entrepreneurs are more extrinsically motivated. This suggests an opportunity to extend the findings of Fauchart and Gruber (2011) about the impact of social identity upon entrepreneurial strategy. Given the cofounds in our sample, further research is needed to tease out the relative contribution of skills and identity upon the opportunity selection, differentiation and other strategies of young firms.

5.2. Implications for Open Innovation

Our study is one of the first to compare the open innovation choices of a sample of young firms of the same age (0-4 years old), in the same industry and with access to the same source of inbound knowledge flows. It suggests some of the ways that the practice of open innovation is different in new firms than with established firms.

In particular, open innovation has been positioned as an ongoing choice to supplement internal R&D (Chesbrough 2003, 2006; Chesbrough & Bogers, 2014), or perhaps to reduce internal R&D capabilities (West & Bogers, 2014). Our data points to a different scenario: open firms that utilize inbound flows *in lieu* of ever having such capabilities. Unlike other studies of firms with technical capabilities that chose to pursue such flows (West, 2003; Henkel, 2006), our open firms were born and built to depend on such flows. Any study of inbound openness choices by new (or small) firms would need to control for those that never had an alternative — while at the same time examining the long-term viability of these dependent firms.

More generally, we extend the conception of open innovation that emphasizes the firm use of knowledge flows (Chesbrough, 2006) by drawing a distinction between different ways that knowledge is embodied. In particular, we develop new measures of inbound openness to distinguish between reuse of knowledge, product components, and entire technological systems. While prior research has emphasized the benefits of knowledge reuse, we suggest how firms with high levels of reuse of external knowledge may excessively constrain their technology and market strategies, particularly for pre-paradigmatic technology and market searches prior to a dominant design.

Our study is one of the few to consider the relationship between a firm's inbound and outbound open innovation decisions. In nearly all (89%) of our cases, the young firms were unwilling to provide more outbound openness than they used in inbound openness. Given their limited resources and the urgent need to generate revenues in a crowded market, these firms selected outbound openness either because they saw benefits to collaboration, or because they were compelled to share by license restrictions on certain inbound flows. However, this was not something that they were willing to do for the benefit of society, their industry or a specific online community.

Finally, our findings have implications for systems integration strategies. Research on complex product systems (COPS) — integration strategies for building hardware systems such as aircraft engines or power stations — has emphasized how firms create advantage through unique configurations of externally supplied components (Prencipe, 2003). Here, the relatively simple designs and wide dissemination of tools limited opportunities for advantage by integrating openly available hardware components; instead, as with open source software (West & Gallagher, 2006), obtaining advantage appears to require producing proprietary components that can be combined with the open components available to rivals. This seems to imply that returns to architectural innovation (Henderson & Clark, 1990; Prencipe, 2003; Baldwin & Clark, 2006) in systems integration have a nonlinear relationship to the complexity of the system. However, more research is needed on integration of open components beyond previously-studied open source examples.

5.3. Implications for Practice

This study suggests both a wide range of inbound and outbound generic openness strategies, providing nuanced alternatives of inbound and outbound knowledge flows that entrepreneurs may not have considered. In particular, entrepreneurs have not only the choice of being open — and in what direction and with whom (Dahlander & Gann, 2010) — but also on the nature of what part of the value proposition knowledge flows out of (or into) the firm.

At the same time, the study suggests caution for entrepreneurs on how they select such strategies. While many of the entrepreneurs in our sample had a well thought-out openness strategy, others appeared to have path dependent constraints created by short-term opportunistic approaches. In a number of cases, the choices made during the first few weeks — perhaps in hopes of quickly shipping a product and generating revenue — constrained their strategy (and likely growth prospects) for years to come. This study suggests the crucial interdependencies between these early strategic choices and other entrepreneurial strategies.

5.4. Limitations and Future Research

The study has a number of significant limitations. While every effort was made to create a comprehensive database, we cannot vouch for how representative it is of the larger population of new entrants. Our interview sample emphasized North American (particularly US) firms, and thus we have less insight into the strategies of new firms in smaller national markets, or for whom access to the (English language) open community knowledge was less valuable.

Our study examined firm strategies during the early, high-growth period of the industry, and might not generalize to periods of industry maturity or consolidation. We cannot rule out that the differences between 3D printing and complex open source software systems (such as the Linux operating system) are due to the stage of industry maturity rather than the difference between hardware and software. We studied consumer 3D printing at a time when the technology is easy to understand, proprietary designs can compete with open designs, and one with a limited use of patents; in this regard, it is more akin to early personal computers (West & Kuk, 2016).

At the same time, unlike entrepreneurs competing with an open source standard such as Linux (Dahlander, 2007), there were at best weak network pressures to conform to the open standard. Future research is needed to establish whether they would generalize to science-based industries (such as biotechnology therapeutics), that also lack network effects but where knowledge flows are shaped by a strong reliance on patents.

As with other research (Hienerth, 2006; Shah & Tripsas, 2007), our study examined user innovators that started companies rather than those that did not. For cases where there are well-defined user community boundaries (as with Hienerth, 2006), future researchers could identify a broader population of innovators and contrast those that start firms with those that do not.

Our study of combining inbound and outbound flows only studied those non-monetized flows typical of community collaborations (Henkel, 2006). Future research could consider how the decisions for combining flows differ when those flows are the monetized flows more often associated with open innovation (cf. Chesbrough, 2003; Dahlander & Gann, 2010).

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7. Figures and Tables

Figure 1: Model of openness decisions

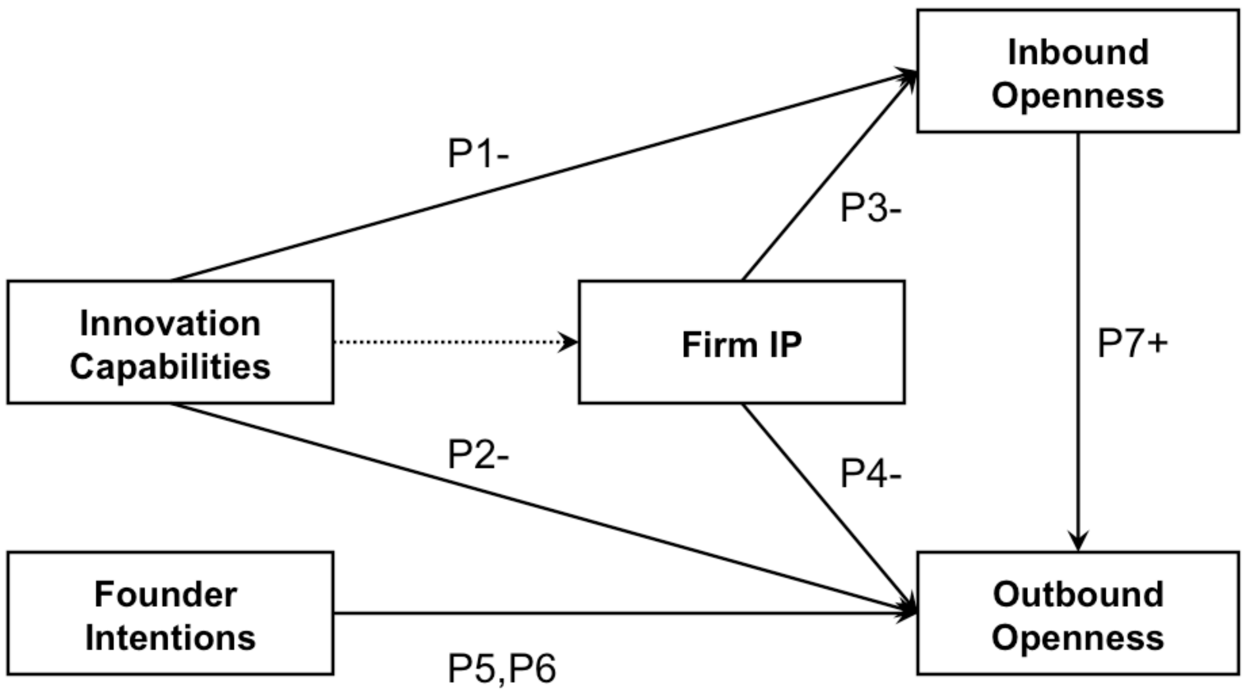
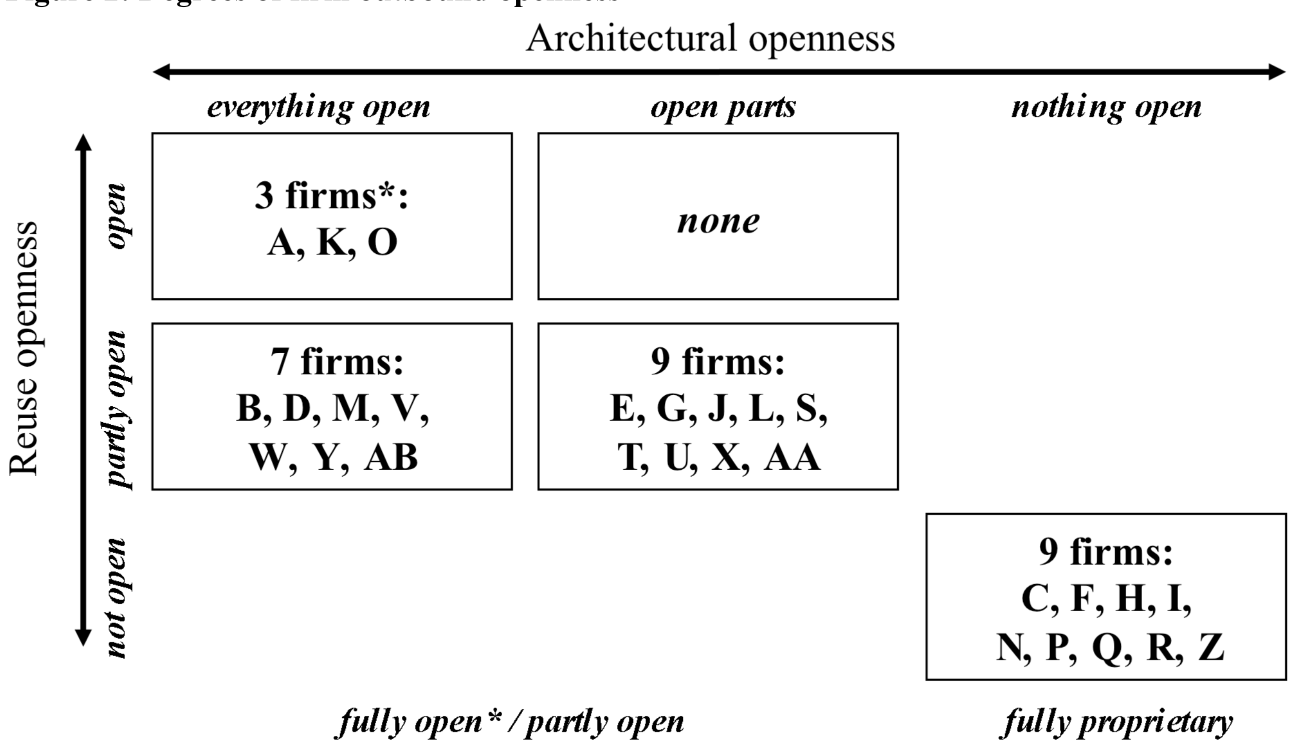


Figure 2: Degrees of firm outbound openness



Note: For confidentiality reason, company names are replaced by letter codes

Table 1: Geographic distribution of companies in sampling frame

	Number of Companies		
Headquarters Location	**Sampling Frame**	**Contacted**	**Interview Sample**
Asia	24	3	1
Europe	50	29	8
North America	65	49	19
Other	5	0	0
Total	**144**	**81**	**28**

Table 2: Description of firms in interview sample

Firm	Location	Founding Date	First Product
3D Monsters	US	2012	2015
AIO Robotics	US	2013	2013
Boots Industries	Canada	2012	2013
Cobot	Germany	2014	2015
Cyrus	Netherlands	2014	2014
Deezmaker	US	2012	2013
DFRobot	China	2008†	2013
DM Industries	Italy	2013	2014
Fabmaker	Germany	2013	2014
Formlabs	US	2011	2013
Full Spectrum Laser	US	2010	2014
HypeCask	Germany	2013	2013
Hyrel 3D	US	2012	2013
Isis3D	US	2012	2012
It is 3D	UK	2011	2012
Kudo3D	US	2012	2014
Kuehling & Kuehling	Germany	2013	2013
Maker's Tool Works	US	2012	2012
Mission Street Manufacturing	US	2012	2014
New Matter	US	2014	2015
NVBots	US	2014	2014
Printrbot	US	2012	2012
Re3D	US	2013	2013
Sedgwick	US	2008†	2014
SeeMeCnC	US	2011	2011
Terawatt Industries	US	2012††	2012
Type A Machines	US	2012	2012
Ultimaker	Netherlands	2011	2011

Legend: † parent company founding date; †† spinoff company founding date

Table 3: Openness and entrepreneurial strategies of interview sample

		Technology	*Linkage to Community Knowledge*		*Proprietary*		*Founder Intentions*	
Openness	Firm	Printing	Inbound Flows	Outbound Flows	Technical Capabilities	Patents	Approach	Startup Intention
Open*	A	FDM	††††	+++	++		User Entrepreneur	Purposeful
	K	FDM	††††	+++	+++		User Entrepreneur	Purposeful
	O	FDM	†††	+++	++		User Entrepreneur	Purposeful
Open architecture, limited reuse	B	FDM	††††	++	++		User Entrepreneur	Purposeful
	D	FDM	†††	++	+		User Entrepreneur	Purposeful
	M	FDM	†††	++	+		User Entrepreneur	Accidental
	V	FDM	†††	++	++		User Entrepreneur	Accidental
	W	FDM	††††	++	++		User Entrepreneur	Accidental
	Y	FDM	†††	++	++		Entrepreneur	Purposeful
	AB	FDM	††††	++	++		User Entrepreneur	Purposeful
Partially open architecture	E	FDM	†††	+	++		User Entrepreneur	Accidental
	G	FDM	††††	+	++	+	Entrepreneur	Purposeful
	J	FDM	†††	+	+++	++	User Entrepreneur	Accidental
	L	FDM	†††	+	++		User Entrepreneur	Accidental
	S	DLP	†	+	++		Entrepreneur	Purposeful
	T	FDM	†	+	++		Entrepreneur	Purposeful
	U	FDM	††††	+	+++		User Entrepreneur	Accidental
	X	FDM	†††	+	+		Entrepreneur	Purposeful
	AA	FDM	†††	+	++		User Entrepreneur	Accidental
Proprietary	C	FDM	†	-	+++	+	User Entrepreneur	Purposeful
	F	FDM	†	-	+++	+	Entrepreneur	Purposeful
	H	FDM	†††	-	+++	+	Entrepreneur	Purposeful
	I	DLP	†††	-	+		Entrepreneur	Purposeful
	N	SLA	††	-	+++	++	Entrepreneur	Purposeful
	P	FDM	†	-	+++	++	Entrepreneur	Purposeful
	Q	FDM	††	-	+++	+	User Entrepreneur	Accidental
	R	SLA	††	-	+++	+	Entrepreneur	Purposeful
	Z	SLA	†	-	+++	+	Entrepreneur	Purposeful

Openness: *Fully open architecture and reuse. *Inbound Flows:* † Learning, †† Software Components, ††† Hardware & Software Components, †††† Systems

Table 4: Firm openness for outbound flows

Outbound Openness	Firm	Representative Quotes
Open +++	A	"Yes, everything we do is all open source. All our CAD files can be found on our GitHub page. The forum is also a page where we talk about designs and changes and upcoming things "
	K	"It is open license. ... it is commercially available, so if people get it you know they can just commercialize it because the [product name] is mostly from the RepRap community."
	O§	"Yes, we release all designs - the complete CAD designs for 3d printed parts are already online, as well as software solutions, also when they are derivatives of existing solutions, such as adapted the firmware for our printer "
Partly Open ++	B	"We operate under an open source licensing paradigm, so all of our printers are published with open source licensing and our plans are completely free to the public. [Firm name] publishes its design on GitHub "
	D	"We are not going to be completely open sourced forever but the [product 1] is completely open sourced, because it grew out of this open source movement."
	M	"[We] are open source, but I am a perfectionist and therefore do not release things until they are high grade or high standards. The first versions are all out there already, but the second one we posted some stuffs … there are little updates that we like to do before we post it, so people do not make a bad machine. They are posted on our wiki at [firm website]"
	V	"[Product name] printers are open hardware, the design files are published for non-commercial use."
	W	"Yeah, so the [product 1] is open source, we actually have two printers now, we have the [product 1] series and we have the [product 2]. The [product 2] is I would call it semi open, it's not a printer that can be manufactured by somebody in the basement and that it is something that requires specialized equipment to make. … So we're happy to share the design [of product 2] with anybody who asks if they want to modify or make changes to it."
	Y	"The [product name] itself is open source. We do provide the drawings, we provide schematics and drawings for the product itself."
	AB	"My full time job is to improve my product. So when I improve, I share back and now you can see my influence on all sorts of companies. … We published the source code parts which is a variation of open source code. We published some parts designed to help people modify the printer."
Opening Parts +	E	"For things that the community can take advantage of, we will open up. For things that the community has no hope of duplicating, we are not going to open it up."
	G	"On the extreme end of our software it is closed source and on the extreme end of our hardware it is closed source, like our actual printer design is closed source. … In the middle areas we are using open source projects."
	J	"We have come from open source, we use open source, and we publish stuff as open source – however we are also taking up patents and not everything we do will be 'open source'. … we're an 'accessible source company'. Some of what we do will be open, some won't."
	L§	"Well, our first printer is completely open source in terms of hardware. … Regarding the new printer, are we still discussing which parts are useful to open up, the firmware will be open for sure, though."
	S	So, what we are planning to do, is first to publish our … perfectly working code."

Outbound Openness	Firm	Representative Quotes
	T§	"We will have a mix of both."
	U	"In terms of hardware, it is definitely not open. In regards to software it definitely is, since we are using the firmware and slicer for example, which are both open source. We join in developing these."
	X	"So I did release the files under those licenses for the...- at the time I had three models – the plastics, fully open source, the laser cut noncommercial, what we call the LC and then a larger version, called the plus, I released all those files, but kept it under a non-commercial for the laser cut versions."
	AA	"We provide the printable parts to the public. So the design file itself, unless you have a laser cutter or a CNC machine you can't use the design file at all because you have to machine them. So in our opinion, unless you are a Chinese company, you won't be interested in having our design file because if someone [has] a CNC machine worth 15,000 euros, he doesn't care about our design file; he's making his own printer."
Proprietary -	C	"No, we never considered open source. The reason it's not open is simple. If we open it up, then piracy will be a big problem and we are not ready to handle that yet but the real reason is too many people will call us expecting us to support it as an open source and we can't do that. We don't have the time to do that. Eventually, the heads will be completely open source I'm certain of it and people don't take that just one person has created the whole machine. A lot of people have given us ideas for the software and I've written a vast majority of the software now but we hold back where we can. You'll see that we do that consistently."
	F	"If we would completely open it up, we would know that there would be another company by tomorrow, which copied our concept a hundred percent."
	H	"We [are] also going to produce a metal-based printer, not a metal printer, but made out of metal — [it] is very difficult to make parts for that through 3D printer. That, we will probably be a bit more protective about the IP of the machine itself."
	I	"As part of the Kickstarter I promised to release it as open source. I have not as of yet officially released open source, but that is my intention and direction."
	N	"We weren't going to try to build a piece of open source hardware…one thing we think is that we can build the best 3D printer through the format that we have right now."
	P	"We evaluated and then concluded that [being open] is not the most cost effective long term solution and that is basically where we stopped."
	Q	"It is open in a sense that people can look at it and try and recreate it. There is no plan to put our designs out there for the world to have."
	R	"I don't think we plan to do so. You mean provide under open source? No I don't think we plan to do so. We do have our own design of the product - we have done it in-house."
	Z	*Had no ties to the community, and didn't see a value in either using or sharing with community.*

§ Quote translated and paraphrased from original language

Table 5: Firm openness for inbound flows

Inbound Openness	Firm	Representative Quotes
Systems Reuse ††††	A	"Yes the first machine that we did on Indiegogo was [product name] and that was a derivative of the Huxley from RepRap."
	B	"My first product was the (company name) MendelMax 1.5, and our first sell was the MendelMax 1.5 kit, which occurred in the month that (company name) was launched, so May of 2012."
	G	"We are clearly a RepRap derivative, if anyone knows how RepRap works. Like any low-cost FDM printer. They are all RepRap-derivatives in my opinion and we are, too."
	K	"No we didn't start from scratch, actually we, let me see, we started from a model called the Ultimaker that is the first generation of the [product name], the second one we based on the Rostock."
	U	*Firm used components and OS printers for prototypes. But for commercial product they designed completely new designs.*
	W	"So in 2012 I designed the [product name] based on the Prusa Mendel and released it as open source."
	AB	"We definitely found a lot of code, parts, prototypes so our initial designs were almost entirely inspired from the open source technologies because we felt that you know one of the principles we use is economy of effort so we felt that there were already some good starting points out there so instead of reinventing the wheel we should just study these and made them better so that's where we started really."
Hardware and Software Component Reuse †††	D	"The circuit board we used - the circuit board and the software are completely from the community."
	E	"The thing that probably influenced the machine most of all is a lot of the hot-end designs and we spent a lot of time looking at the open source hot-ends and analyzing their behavior and replicating some of the features and doing things differently, coming back and forth."
	H	"Yes we did source some of the stuff from the RepRap community. "
	I	"I took, sort of from scratch. … I mean, just found ways to manufacture different parts of it better and faster and cheaper while higher quality."
	J	"We didn't have to develop any electronics, we didn't have to develop a hot end, we didn't have to develop any firmware, didn't have to develop any software. Literally to be able to bring the first machine to market - all we had to do was design all the mechanical, that's it."
	L§	"The impact of open source on (printer name) was relatively large. The extruder is, for example, an extruder after MakerBot. The XY structure is like Mendelmax, as is the Z-axis."§
	M	"[We kept] the basic concept. It follows the same axis, the Y has its own motor, the X has its own that goes up on a Z. That is pretty much like the Prusa Mendel and a handful of other designs."
	O§	"We have developed a lot in the area of the extruder there.… Since then we have revised the main core components at Prusa and redeveloped."§
	V	*The firm designed a new system but used a lot of open components.*
	X	In the very beginning, I was the benefactor of the work that the RepRap community did. [...] We stood on the shoulders of giants.
	Y	"The controller board itself is the Azteeg, but I do not believe that it is open source itself, just derived from components in the open source community, and using the Arduino programming platform, so, again on the software it is open source.… As far as the mechanical design goes, it was created from scratch"
	AA	"Yeah the only thing that's actually derived from open source is the electronics which is basically the brain you could say. I mean the rest of it, the design is ours."

Inbound Openness	Firm	Representative Quotes
Software Component Reuse ††	N	"Certainly we believe in open source software. In case of software, that model does work for a lot of different types of software and we use a lot of open source software and we've contributed back to a few projects."
	Q	"We have used every single [open source] package that is out there, looked at how they worked and figure out what makes sense and what does not makes sense, in different applications and in some cases, said, 'What the community has done is just insufficient for our needs, because it does not fit with our data structures, our server architecture, so we had to re-engineer a lot of it.' "
	R	"So for example software wise we're using open source right now. We're using Printerface for the host software. We are using Slic3r for the slicing. … I think the DIY community is kind of very supportive and giving tips..."
Learning Only †	C	"When we looked out there we found very little that we would like to use. ... We wrote all the firmware ourselves. We used and started with Repetier host as a base for controls."
	F	"Because of the experience we made is why we developed the [printer]. It was pretty much a transition from the RepRap community."
	P	"The first prototypes that we have made for testing have used open source software and controllers. None of the hardware was open source. We did not start with a RepRap or anything. We always developed our own mechanisms. For speed of prototyping, we have used open source and other off the shelf [components] but closed source software and electronics."
	S	"We have to develop basically from scratch. When we started, there was very little references to start with. … Now things are changing, you can actually find much more material to start off, so this is the thing that is changing in the last year. At our time, do not have many references to start."
	T§	*Reused open source components and OS printers for prototypes, but developed completely new designs for commercial products.*
	Z	"Software is usually written by professionals or designs made by professionals and then we had better results."

§ Quote translated and paraphrased from original language

Table 6: Firm technical capabilities

	Technical Capabilities		Degree of inbound flows	Degree of outbound flows
Firm	**Experience & Education**	**Level**	**Level**	**Level**
C	Multiple years of 3D Printing industry experience	+++	+	-
F	PhD students in Robotics	+++	+	-
H	Over 15 years of working experience with 3D printers	+++	+++	-
N	Technical degree from MIT and tinkerer in makerspace	+++	++	-
P	Degree in mechanical engineering and 3D printing customer	+++	+	-
K	PhD in Robotics	+++	++++	+++
Q	Master's in mechanical engineering, focused on 3D printing	+++	++	-
R	PhD in Electrical Engineering	+++	++	-
J	Multiple years of job experience in 3D Printing	+++	+++	+
Z	PhD in Mechanical Engineering & Physics	+++	+	-
U	PhD Polymer Chemistry, Industrial Engineering	+++	++++	+
AB	Computer Science, Mechanical Engineering, Aerospace Engineering	+++	++++	++
A	CNC programmer and general machine tool background for twelve years	++	++++	+++
B	Software expert and tinkerer	++	++++	++
E	Software developer	++	+++	+
G	Mechanical and aerospace engineer	++	++++	+
L	Industrial design student with engineering background	++	+++	+
O	Mechatronics students	++	+++	+++
S	Software and electronic background	++	+	+
T	Mechanical engineering background	++	+	+
V	Master in Information Management	++	+++	++
W	Tinkerer in hardware and software	++	++++	++
Y	Work experience in manufacturing	++	+++	++
AA	Experience through tinkering	++	+++	+
D	Music degree	+	+++	++
I	Working experience in retail	+	+++	-
M	Work experience in the film industry	+	+++	++
X	Bible and literature degree	+	+++	+

Table 7: Evidence of founder intentions

Founder Intentions	Classic Entrepreneur	User Entrepreneur
User Entrepreneurship	"I decided that I wanted to start a 3D printing company.…I started with one idea, which was basically about how to do large-format / large-size 3D printing and it did not seem like that was very commercially viable, but I was still a business student this whole time." (G) "I founded the company … after the better part of year prior to that doing R&D and really evaluating whether consumer 3D printing could potentially be a market worth going into." (P)	"I actually started using, and troubleshooting 3D printers in mid 2011, at my local hacker space … I had already been working with 3D printers and was fascinated that the 3D printers are going to bring changes on a scale similar to what Internet has done." (B) "My business partner and I built a (printer name) for a completely unrelated project. … We both immediately got the sense that this was a really fascinating technology with a lot of potential and implications." (D) "We first started the company because we wanted to build our own 3D printers after playing with other commercially available printers that we had. And we thought we could … do a better job." (AB)
	Purposeful Entrepreneur	**Accidental Entrepreneur**
Accidental Entrepreneurship	"I felt [the 3D printer] was going to be a game changer for society in general, similar to the impact that the internet has had on society, so I felt that was something I wanted to jump on the tech curve as early as possible." (B) "When we got it together, we started talking about how … this could really go somewhere" (D)	"I was just talking to them about that and what I was doing and what was going on. One of the guys says - well you know, if you build one – I would love one for me, too." (E) "And at that point I was looking at Kickstarter. Some 3D printers were posted up there. One previous printer did really well on it. I thought this might be really cool as a hobby." (M)

8. Appendix 1: Interview Protocol

1 Background of the firm and founders

1.1 When and how was the company founded?
1.2 Who were the founders? Did any have a background in 3D printing? Did any have ties to a local makerspace or fab lab?
1.3 How did you get funded? How much did you raise?
1.4 What were your goals in creating the company?
1.5 What was your first product? First revenue? First printer?
1.6 Do you provide schematics or designs for your printers? How? Are they available under a public license?

2 Connection of the startup to open hardware communities

2.1 Are any of the founders or employees involved with an open 3D printing community such as RepRap? Another open source or open hardware community related to 3D printing?
2.2 Was your first product derived from or influenced by open hardware designs [such as RepRap]? What specifically influenced which part of the design?
2.3 What role have the community and community designs played since then? Please name specific products, parts and open designs.
2.4 To what degree do you benefit from hardware or software components that are also used by the open hardware designs?
2.5 How is your product better than (or different from) the open design? How did you come up with these improvements?

3 Questions for those working with the RepRap community

3.1 To what degree do other aspects of your business (marketing, market research, support) benefit from working with open hardware communities?
3.2 Overall, did working with the open hardware community make it easier for you to launch your company or gain access to the market, i.e. to overcome barriers to entry?
3.3 Did working with the open hardware community impact the liabilities of newness and smallness that your company faces?
3.4 Are there any negative impacts of working with these communities or designs?

4. Questions for those not working with RepRap

4.1 Did you consider working with one of the open hardware communities such as RepRap? Why did you decide not to do so?
4.2 What disadvantages do you see in working with such a community?
4.3 Which advantages do you see in working with such a community?
4.4 Do you compete with any companies that are using designs derived from RepRap or another community? How does this impact your competitive position against them? How do you respond?