The Complementarity of Openness: How MakerBot Leveraged Thingiverse in 3D Printing

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Abstract: *Selective openness allows a firm to sell a systemic innovation that combines both open and proprietary technologies. Such firm strategies are now common for open source software and other information goods. However, they pose conceptual and practical uncertainties for hardware-focused companies, particularly as research on open hardware has emphasized community rather than firm success. Here we study firm openness in 3D printing, with a case study of how MakerBot Industries leveraged external communities and selective openness become the consumer market leader. After reviewing the literature on systemic innovation and selective openness, we document the proprietary strategies of a dozen startup companies during the first two decades of the 3D printing industry. We contrast this to the open hardware, software and content strategy that MakerBot's founders used to enter and grow the consumer market from 2009 onward. We show how MakerBot shifted to a selectively open, systemic innovation strategy that complemented proprietary hardware and software with open user-generated content from its Thingiverse online community. From this, we suggest the inherent complementarity of selective openness strategies between open and proprietary components, and conclude with predictions as to when and how a startup or incumbent firm will combine open and proprietary elements.*

Keywords: 3D printing; online communities; open innovation; open design; complementary assets

1. Introduction

For decades, the incentives to create and diffuse innovations have been associated with the strength of appropriability regimes and the ability of a private inventor to appropriate private returns from their economic investment. Traditionally such incentives are subject to strong IP protection mechanisms such as patents, copyright and trade secrets (Nordhaus, 1969; Teece, 1986).

Over the past decade, some previously proprietary incumbent firms have experimented with opening parts of their complex offerings to win cooperation from adopters, complementors and even rivals (West, 2003; Henkel, 2006; Shah, 2006; West & Gallagher, 2006; West & O'Mahony, 2008; Spaeth et al, 2010; Henkel et al, 2014). The availability of shared IP from an open source community has also enabled the formation and entry of new firms that build upon these collective efforts (Gruber & Henkel, 2006; Dahlander, 2007).

Prior studies have emphasized openness in software, endowed with the characteristics of information good. Therefore, we would expect the findings in software to representative of the larger class of information goods, which are nonrivalrous in consumption and have little or no marginal cost, making them nearly costless to disseminate (cf. Varian, 1998; Kogut & Metiu, 2001; Cusumano, 2004; von Hippel and von Krogh, 2003). However, limited research on open hardware communities has suggested that their economics and organization are quite different (e.g., Raasch et al, 2009), and thus a goal of this paper is to extend our understanding of these communities to explain how firm strategies leverage these communities.

Here we examine how openness influenced the success of 3D printers, an industrial technology from the 1980s that faced slow adoption until the RepRap open hardware project stimulated the subsequent entry of consumer-focused startup producers. We focus on the case of MakerBot Industries, the leading maker of consumer 3D printers, with its unique value creation strategy. The firm was founded based on an open source hardware and software strategy —

complemented by its Thingiverse open content community — and kept its user-generated content open even after it switched to proprietary hardware and software.

From this, we extend the research on selective openness from software to hardware business models. Specifically, we propose an extension of the open source model to suggest a more general pattern of what we term the *complementarity of openness.* In such cases, openness increases the value of the non-open part of a firm's value proposition, and thus a firm can only be open if it has something that is closed which allows it to generate revenues and profits to support the business. We also highlight the unique selective openness constraints of new firms, that leverage open technologies to create value and enter markets while seeking proprietary imitation barriers to protect value capture. We offer specific predictions as to how resource limits will influence a new firm's openness strategies, and also suggest which parts of a complex offering will be selectively opened (or closed).

The paper begins by reviewing the relevant theoretical literature, and then summarizes the technical and market context of late 20th century industrial 3D printing that enabled a rash of consumer-focused startups in the early 21st century. We review the evolution of the MakerBot product and content strategies, and from this suggest testable propositions, other theoretical implications and opportunities for future research.

2. Open Strategies for Systems, Communities

The value proposition for consumer 3D printing requires two complementary offerings: systems and content. Consumer value is realized when digital designs are transformed into physical objects using a system that includes graphics software, a computer and a 3D printer. Content means the creation, modification and sharing of these digital representations of tangible objects — often shared through online communities. Digital designs are complementary goods that make the adoption of 3D printing systems more valuable.

Here we review research on the role of complementary goods in systems adoption, with a focus on community-sourced complements. We also consider how firms interact with external communities, and selectively provide outbound openness (and accept inbound openness) to advance firm goals, particularly in the context of open source software and hardware.

2.1 Complementary Goods and Systems Adoption

Innovations are adopted based on their characteristics, and also the characteristics of their adopters. In particular, earlier adopters (such as hobbyists or other enthusiasts) are more eager to try new technologies without proven benefits and are tolerant of usage difficulties (Rogers, 1995). For many products, the value of the innovation depends on the provision of certain complementary goods that make the innovation more valuable (Teece, 1986).

The creation and adoption of a technological system is different from other kinds of innovation, in that the value received by the adopter depends on the value of the overall system. Promoters of such systems innovation face the challenge in combining and coordinating the production and adoption of different components of the system by external actors (Maula et al., 2006). Although systems innovators can attract a variety of complements, it is difficult to align external actors and processes. In relation to open innovation, systematic innovation entails boundary management (Jarvenpaa & Lang, 2011; Teigland et al., 2014) within and across the borders of firms. Open innovation research only partially explains how firms may combine open and proprietary components that are subject to different licensing regimes (West, 2006).

A particular type of systems innovation is a platform, which has two key attributes. The platform provides well-defined interfaces that enable third parties to provide complementary goods (such as “apps”) for the platform, and the platform sponsor nurtures an ecosystem of firms (or individuals) who supply such complements (Bresnahan & Greenstein, 1999; Gawer, 2009). Sponsors selectively provide openness — in some parts of their technology but not others — to attract both adopters and a supply of complements while retaining enough proprietary control to extract profits from the platform (West, 2003; Boudreau, 2010; Eisenmann et al, 2011).

External user communities have been increasingly important to firms in industries organized around digital goods. Firms can tap external communities as part of an open innovation strategy (Spaeth et al, 2010; West, 2014). Such communities provide a source of complementary goods, particularly for information goods such as online information (Nov, 2007), musical sounds (Jeppesen & Frederiksen, 2006) and video games (Jeppesen & Molin, 2003). Online communities can also provide support (Lakhani & Von Hippel, 2003), bug reports (Dahlander & Magnusson, 2008) and marketing feedback (Schau et al, 2009). For would-be entrepreneurs, the firm-sponsored communities of today’s “app economy” provide an opportunity to develop and diffuse new add-on products (MacMillan et al, 2009).

2.2 Selective Openness

Firms often choose to be selectively open in dealing with external actors (Alexy et al 2013). Because too much revealing may erode competitive advantage and enable competitors, they open part of their overall offering (such as a module within a complex system) or provide partial openness for a broader part of that offering (West, 2003). They freely reveal information that could also induce potential rivals to follow a similar openness strategy, particularly for information that is less strategically important (Henkel, 2006; Henkel et al, 2014). At the same time, their willingness to be open may be limited by their ability to appropriate value from the non-open parts (West, 2006).

Over the past 15 years, most of the experimentation in (and research on) firm openness has focused on open source software. Firms have worked with and created external online communities that create free and open source software (Lakhani & von Hippel, 2003; Shah, 2006; Dahlander & Magnusson, 2008). Such communities are characterized by a standard form of IP license, a form of cooperative production and a mechanism of governance (West & O’Mahony, 2008). The license allocates rights to use and modify IP for community members and non-members alike (Perens, 1999).

For systems adoption, these communities can provide the core functionality of a system, enabling firms to sell higher-value proprietary complements. Conversely, firms may choose to offer a proprietary platform and seek open source donations of complements (West & Gallagher, 2006). Overall, such communities provide an important source of open innovation for firms (West & O’Mahony, 2008; Piva et al, 2012).

Open source communities have enabled the creation of new firms, by providing the technology necessary for entrepreneurial entrants to provide new offerings (Gruber & Henkel, 2006; Dahlander, 2007; Piva et al., 2012). In many cases, these firms create their offerings by “forking” off a proprietary version from the community’s shared source code. Entrepreneurial companies have also created communities, enforcing selective openness through rules that keep the community activity aligned to support the firm’s objectives (Dahlander & Magnusson, 2005; West & O’Mahony, 2008).

While technologies from open source communities reduce firm entry barriers and enable value creation for customers, the open technologies reduce the opportunity for uniqueness and thus value capture. In responses, firms developed complex offerings that combine open (commodity) and closed (proprietary) components, while embedding this value proposition in value networks (West & Gallagher, 2006; Morgan & Finnegan 2014). Success requires accessing external knowledge of new or established communities, while structuring the rules inside and outside to constantly realign the community efforts with the firm's goals (Dahlander & Magnusson, 2008; West & O'Mahony, 2008).

Enthusiasts have sought to replicate the success of open source software communities to produce tangible goods including electronics and hardware. These efforts are often organized using processes and principles directly modeled on open source software. This includes modularization to minimize complexity, adapting open source IP licenses, a culture of collaboration, and the selective use of openness by project sponsors. Compared to the production of software or other information goods, however, open source projects producing hardware have higher barriers to entry and collaboration inertia, and a greater need for an external sponsor (typically a single firm) to provide essential infrastructure such as manufacturing (Balka, Raasch and Herstatt, 2009, 2010; Raasch, Balka & Herstatt, 2009).

As with open source software, the initial research on open source hardware emphasized community success. Unlike research on open source software (e.g., the work of Dahlander, Henkel, Piva, West and others), little (if any) research has considered how firms achieve their strategic objectives by working with these hardware communities. As Raasch and her colleagues have shown, the differences between software and hardware participation and replication costs (among other differences) lead to important differences in strategies for community success, and thus we would expect similar (if not exactly parallel) differences in strategies for firm success.

This paper examines this latter topic: firm strategies for leveraging open source hardware. In particular, we focus on two specific questions. First, how do new firms leverage open hardware communities? Second, how does an open source hardware firm combine open and proprietary elements of their business model to create value while creating sufficient barriers to allow the firm to capture value?

3. Research Design

We examine the history of consumer 3D printing (3DP) within the settings of 3DP industry, focusing on the unfolding of major events over time as a key aspect of this process. In doing so, we can illuminate the relationships between software and hardware, and between information and tangible goods. As tangible goods, 3D printers play a unique role in bridging the digital and physical worlds by providing a way to transform digitally stored representations of objects into a tangible good.

This fundamental relationship and basic 3DP technology were 20 years old before the first consumer 3D printer was sold. We thus sought to explain why the consumer vendors emerged when they did, and how their IP and product strategies were different from those of their industrial forbears. The influence of an early 3DP open source hardware community also allows us to study how the openness strategies of these 3DP vendors are similar to or different from the often studied open source software companies.

To better develop theory and be able answer "how" and "why" questions, we employed an exploratory research approach using a qualitative case study (cf. Yin, 2003; Eisenhardt & Graebner, 2007). To understand the consumer segment, we use a case study on MakerBot

Industries, which we chose for three reasons. First, it is one of the most successful consumer 3DP firms: the best known in the US, the global market share leader, and the first to reward its founders with a successful exit. Second, its founders were first to establish a consumer-oriented digital content community to complement the value created by 3D printers. Third, MakerBot used two distinct IP strategies for its 3DP systems, shifting from mostly open to a mostly proprietary approach. We believe that MakerBot thus fits the guidelines of Yin (2003) for unique cases in single-case research designs, and the case selection advice of Eisenhardt and Graebner (2007: 27) for a case that is "unusually revelatory, extreme exemplar" and "particularly suitable for illuminating and extending relationships and logic among constructs."

We examine MakerBot's first five years of existence (January 2009-January 2014) — which includes its entire period as an independent company and its first few months after acquisition — and also the parallel existence of Thingiverse (an online content community with overlapping founders) during this same period.

We used multiple sources of evidence as recommended by Yin (2003). The case study utilizes secondary data, and archival primary data. Information on the origins of the industry and technology is taken from a variety of secondary sources, including technical articles and books (e.g. Jacobs, 1992), news articles, FundingUniverse.com, company websites and patents; particularly helpful were the annual reports on 3D printing by Wohlers Associates.

To avoid retrospective biases (Eisenhardt & Graebner, 2007), the primary data includes contemporaneous reports of key executive motivations, as captured by published interviews (Stern, 2010) and first hand accounts (e.g. Smith, 2008; Pettis, 2010). Information on the RepRap Project, MakerBot and Thingiverse were taken from the community wikis and discussion group. Key postings of the RepRap Project from 2005-2011 are compiled in Hodgson (2012). The evolution of the Thingiverse web site was analyzed using the Internet Archive (archive.org).

To provide internal validity, we used pattern matching in the data to build possible explanations (Yin, 2003). In particularly, we analyzed the secondary and primary data to develop a historical narrative of the relationship between MarketBot and Thingiverse. This approach sensitized us to the complementary relationship between software and hardware. For MakerBot, the study examined all 3D printer models released during the study period, as well the associated software offerings during this same period. In our analysis, we focused on the inflection points — places where the strategy changed, particular in the degree of openness — and thus sought to understand the strategy before and after each inflection point.

For Thingiverse, there were no corresponding discrete inflection points. We thus sought data that captured the high-level differences among content and participant categories in the community, as well the secular growth of the community during the relevant period. In doing so, we drew upon the broader perspective developed by the second author during a three year study of the Thingiverse community.

4. Origins of Consumer 3D Printing

The term 3D printing refers to a family of technologies that allow the translation of digital designs into physical objects via a computer-controlled custom manufacturing device. While "3D printing" once referred to a specific process invented by MIT, today the term is used more generically to include a range of additive manufacturing technologies.[1]

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[1] The summary of the key technologies is taken from the technical literature, including Wohlers (1992), Jacobs (1992; 1996), Kruth et al (1998), and Gibson et al (2010).

The industry and technology had two distinct phases and markets (Table 1). The first 20 years were limited to industrial and commercial[2] vendors, who used patented technology to sell hundreds (later thousands) of units every year at prices exceeding $100,000. The consumer market was created and grew explosively after 2005 in response to three factors: the "maker" movement of do-it-yourself hobbyists, the formation of the RepRap open hardware community, and the entry of dozens of startup firms selling low-priced printers (priced less than $5,000) after the 2006 expiration of a key industrial patent. As a result, in 2013, consumers bought more personal printers than were purchased by industrial buyers in the first 25 years. As with computing and other technologies that shifted from business to consumer buyers, the shift required adapting the technology to be simpler and less expensive.

To understand MakerBot's strategies and growth, we review the technology and business models of first decades of the 3DP industry, and then discuss how they were adapted by the consumer 3D printing firms of the 21st century.

Insert Table 1 here

4.1 Invention and Industrial Applications of 3D Printing

A series of additive manufacturing technologies were invented in the 20th century, most by U.S. inventors during the late 1980s (Table 2). During this period, none emerged as a clear dominant design that displaced the others, with market share fragmented between multiple technologies. All of these approaches involve creating a 3-D object as a series of thin two-dimensional layers, one on top of another. These technologies were created by academic, corporate or individual inventors, many of whom went on to found startups to commercialize the technology (Table 3). These 3D printers had three initial applications: rapid prototyping, making molds for high-volume production and direct short-run production.

Insert Table 2, Table 3 here

Two of the major technologies involve having light focused to solidify the input material at a specific location. Stereolithography (SLA) involves shining an ultraviolet light on a liquid resin to harden the liquid into plastic at a particular location. It was invented by Chuck Hill, who left his employer to found 3D Systems.

In parallel, Carl Deckard (a PhD student at UT Austin) invented Selective Laser Sintering (SLS), which uses an infrared laser to fuse a plastic or metal powder. It was an important as the first technology to directly produce metal objects. UT Austin was granted a series of patents beginning in 1989, and licensed the patents to a number of spinoff firms. Deckard cofounded DTM Corporation, which operated a 3DP service bureau starting in 1988 and sold its first printer products to industrial customers in 1992.[3]

Others adapted 2-D inkjet printing to build up 3D objects. This included MIT professor Emanuel (Ely) Sachs, who with his researchers was granted more than a dozen patents from

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2 While most of the early systems were sold to industrial manufacturers, a few systems (such as those by Solidscape née Saunders) targeted commercial customers such as jewelers and dentists.

3 Other metal fabrication techniques emerged in the 1990s. Independent inventor Ralf Larson worked with Chalmers University of Technology to replace the laser of SLS with an electron beam and create Electron Beam Melting (EBM), while other researchers modified FDM to use spools of metal filament.

1993 to 2006, in a process called "3D Printing"[4] that MIT licensed to eight spinoff companies in the 1990s (Shane, 2000). Other variants included Inkjet Printing, a low-cost system from Sanders Prototype for printing wax molds for jewelry and dental applications, and PolyJet, used in printers from Israel's Objet to print hundreds of rows of photo-sensitive polymer plastics.

An even simpler approach came from S. Scott Crump, who after tinkering with making objects with a glue gun formed Stratasys in 1988, filing his first of many patents in 1989. The Fused Deposition Modeling (FDM) combined the mechanical advantages of the nozzle approach of inkjet printing with a stable feedstock (a spool of plastic). Finally, Michael Feygin cut and layered paper sheets to create wood-like structures in a process called Laminated Object Modeling (LOM); Feygin formed Hydronetics (later Helisys) to commercialize the technology and (like DTM and MIT licensee Z Corp) received early SBIR funding from the NSF Strategic Manufacturing Initiative.[5]

In the industry's first decade, two companies — 3D Systems and Stratasys — were able to go public, gaining both one-time and ongoing access to capital, as well as increased public visibility. Helisys went public in 1996 but lost money until it failed in 2000. The surviving first generation companies were acquired between 2001-2012 by one of the two market leaders.[6]

In its first five years, 3D Systems captured 73% of the global market by unit sales (Wohlers, 1992). However, it struggled for years to find a large enough market to support its growth and generate consistent profits (Pendleton, 1994; Brooks, 1997). It took a decade of product sales, until in 1997 more than 1,000 systems units were sold worldwide in a single year; in that same year four technologies (SLA, IJP, FDM, LOM) each had between 15-26% market share, with Stratasys the market leader with a 25% share (Kruth et al, 1998).

In 2013, 3D Systems and Stratasys remained by far the largest 3D printing companies, with respective revenues of $513 and $484 million and year-end market capitalization of $9.6 and $6.6 billion. Together they accounted for 73% of the industrial printers sold that year (*Wohlers Report* 2014).

4.2 Consumer Market

For years, futurists and other analysts predicted that 3DP would become cheap enough to become available to consumers. For example, from 2010-2012 the world's largest printer manufacturer, Hewlett-Packard, sold a $17,000 FDM printer manufactured by Stratasys. By 2013, the consumer segment had developed to the point that dozens of hobbyist-oriented models were sold at prices ranging from $300 to $3000 (*Make*, 2013).

As with personal computers, penetration of the consumer market began with the hobbyist market, in this case dedicated aficionados of what during the early 21st century was termed the "maker" movement (Anderson, 2012). Consistent with Rogers (1995), these earliest adopters were (when compared to other consumers) the most motivated and tolerant of performance limitations, complexity and (relatively) high costs.

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4 According to US Patent & Trademark Office databases, MIT also applied to trademark "3DP" and a 3DP logo in 1992, but abandoned the application in 1994.

5 In addition, the creation of SLS at U. Texas and 3DP at MIT were funded by NSF research grants (Weber et al, 2013).

6 When Stratasys merged with Objet in December 2012, their respective shareholders split the combined equity 55/45. The successor company kept the Stratasys's name and NASDAQ stock listing but, like Objet, was incorporated in Israel.

However, the eventual consumer market for 3DP was enabled by the diffusion of technology (and concomitant cost reduction) provided by a 3DP open design community. The RepRap Project was announced in March 2005 by Adrian Bowyer, a UK mechanical engineering professor. He used the commercial Stratasys printer in his lab both for experiments and to fabricate parts, and used his prior 3DP experience to suggest a variety of nozzles for an FDM-based system that would be considerably less expensive (although slower and lower resolution) than existing industrial 3DP systems.

As the first Stratasys patent was approaching its 2006 expiration date, Bowyer created IP rules for RepRap consistent with open source software and open design communities (cf. West & O'Mahony, 2008; Raasch et al, 2009). In his initial announcement on the RepRap.org weblog (Hodgson, 2012: 1-5), Bowyer said a major goal was to put "ideas into the public domain as soon as possible, to ensure that they are unpatentable"; he sought contributions that were free both in price "as well as in freedom", a nod to the free software ideology of Stallman (2002).

To enable hobbyist participation, a major milestone was using a RepRap printer to make another printer; the first such copy was made in 2008. RepRap thus appealed to do-it-yourself hobbyists, variously referred to as "DIY", "makers" or hardware "hackers".[7] Bowyer formed an online community to develop and refine the hardware designs using the RepRap.org website. The community built printers using a variety of open source software and hardware tools.

Over its first five years, the RepRap Project focused on reducing cost and improving performance of the open hardware design. Consistent with other user communities (cf. Lakhani & von Hippel, 2003), it also allowed users to share knowledge about 3DP usage, beyond designing improvements to the RepRap open hardware. In particular, community members identified possible sources of open source and other free[8] 3D design software that would replace the $1000+ CAD packages used by industrial designers and engineers (cf. Hodgson, 2012).

As with open source software (cf. Rossi, 2006), the open source hardware community of user-innovators focused on "scratching an itch", i.e. eliminating barriers to their own use of a 3DP system. As with OSS, they spent less time addressing problems that impacted ordinary consumers: in particular, hobbyists had a higher tolerance for ease of use problems (of the hardware, software and entire system) than would the average consumer.

Also in parallel to open source software (cf. Dahlander, 2007), the availability of open hardware enabled entry by firms. Most utilized the same FDM technology as RepRap in their products, competing with each other and the RepRap open hardware. Some sold RepRap-derived designs: Bowyer himself founded one such company, RepRap Professional, which launched its first product in late 2011. Other firms such as Deezmaker and Ultimaker used what they learned from the RepRap project to create their own designs[9]. Many of these companies had their initial production runs crowdfunded by fundraising campaigns on Kickstarter (e.g., Formlabs) or Indiegogo (RepRap Pro). In 2012, the largest industrial 3D printing company (3D Systems) launched a consumer-oriented Cube printer line.

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[7] The maker movement was organized through *Make*, a magazine first published in 2005 by O'Reilly Media, a San Francisco Bay Area company that published numerous books on open source software.

[8] Community members emphasized software that used both open source licensing and community production processes (cf. West & O'Mahony, 2008). However, 3DP hobbyists also used limited-functionality versions of proprietary software provided free by commercial software companies such as Autodesk and Google (*Make*, 2013).

[9] Bock et al (2014) identify more than 120 startup companies in consumer 3D printing from 2006-13.

The global market share leader among consumer 3DP companies was MakerBot Industries, which offered its first printer in 2009 (*Wohlers Report,* 2013) and controlled the Thingiverse content community. When combined with its own custom software, the company was the earliest to offer an end-to-end system of hardware, software and content for hobbyists and other consumer users. By the end of 2013, it had sold nearly 44,000 printers and had grown to 450 employees worldwide (Biggs & Kumparak, 2014).

5. MakerBot

In January 2009, MakerBot Industries, LLC was founded in Brooklyn by Adam Mayer, Bre Pettis, and Zachary "Hoeken" Smith. The three were active members of NYC Resistor — a "hackerspace" for the New York City DIY community; Smith was also active in the RepRap online community. Pettis became the CEO, Smith focused on hardware and Mayer on software.

MakerBot developed a series of printers based on both the RepRap printer design and RepRap-compatible object designs distributed via Thingiverse. From its open design roots, the company adopted an increasingly proprietary strategy to differentiate itself from the RepRap open hardware and other consumer-oriented 3D printer companies. This included both proprietary hardware components to improve the performance of its printers, and new proprietary software applications to improve the overall ease of use of its system.

To fund their first product, the founders raised $50k from a local entrepreneur and $25k from Adrian Bowyer, founder of RepRap (Pettis, 2011). After an undisclosed angel round, in August 2011 the company became the first consumer 3D printing company to receive venture capital with a $10 million in Series A venture funding;[10] soon after that, both Mayer and Smith left the company. In August 2013, MakerBot was acquired for more than $450 million by Stratasys, the second largest maker of industrial 3D printers.[11] The respective company CEOs vowed that MakerBot would continue to be run as a separate division.

5.1 Hardware: From Open to Closed Hardware

During its 56 months of independent existence, MakerBot developed five consumer-oriented printers (Table 4). All were PC-controlled printers derived from the RepRap designs, and (like RepRap) used the FDM approach of melting a plastic filament from a spool.

Insert Table 4 about here

Only two months after they launched their company, the founders used the annual South by Southwest (SXSW) conference in Austin to unveil their first product: Cupcake CNC, a $750 kit to assemble a 3D printer. The design was based on the RepRap open hardware design, but moved the base rather than the printing head to reduce complexity and weight. MakerBot shipped its first batch of 20 orders in April 2009, and by the end of the year, increased its monthly production batch to 150 units per month (Stern, 2010).

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10 Contrasting MakerBot to one of its rivals, in Fall 2012 Formlabs received $2.9 million from 2,068 backers in one of the most successful crowdfunding campaigns in Kickstarter history. After MakerBot was acquired, in 2013 Formlabs received $19 million in Series A funding.

11 The 4.7 million Stratasys shares offered for MakerBot were valued at $403 million when the deal was announced on June 19, but were worth $455 million when the acquisition completed on August 15. The purchase also included an additional 50% stock dividend incentive based on performance through the end of 2014 (Stratays, 2013). By comparison, the 1994 Stratasys IPO raised less than $6 million.

MakerBot built its hardware based on Arduino, an open source electronics controller technology. It made the design of its first printer publicly available using the same free software license (the GNU General Public License) as used by RepRap. The GPL meant that all hacker changes had to be shared back with MakerBot. The same license was also used with its second product, the Thing-O-Matic, which was released the following year in both kit and assembled form. In an interview, Pettis cited the benefits it gained from open hardware designs:

> Because we're open source and the community is so smart, we've seen a lot of participation in the research and development sector. … Because we're open source, our users know that the code and designs are theirs to hack on. They also know that if they improve their machine, they can share their improvement and everyone in the community benefits (Peels, 2010).

Endorsing this open approach, Pettis criticized an entrepreneurial hardware designer who was selling a derivative of MakerBot's RepRap board without sharing her changes:

> Open Source Hardware is hardware that has an open license. You can copy it, develop it, and even sell it yourself. You must provide attribution to the designer and you must also release the derivative source files under the same license.…
>
> Sometimes an individual or a company makes a derivative of an open source project, goes to market with it and then doesn't share their derivative designs with their changes. This is not only against the license, but it's also not ethical. It is a dead end for the innovation and development which is the heart of the open source hardware community. …
>
> At MakerBot, we take open source seriously. It's a way of life for us. We share our design files when we release a project because we know that it's important for our users to know that a MakerBot is not a black box. …When people take designs that are open and they close them, they are creating a dead end where people will not be able to understand their machines and they will not be able to develop on them (Pettis 2010).

In January 2012, MakerBot made several major changes in its product strategy with the first of its Replicator products, named for the ubiquitous fabrication device of the Star Trek television show. While the product design was publicly available, the design was provided under a Creative Commons license, a less restrictive license. With the Replicator, MakerBot stopped selling printer kits, and only offered assembled products, emphasizing ease of use and reliability. The Replicator models also offered enclosed cases that reduced the risk of having the printer catch something while printing. These attributes supported the company's stated "mission to bring MakerBots to the desktops of everyone" (Bilton, 2012).

However, in September 2012, MakerBot reversed its IP strategy with the Replicator 2. Unlike the previous products, the design of the Replicator 2 (and all subsequent printers) remained a trade secret, just as the design of earlier industrial 3D printers had been a trade secret. Pettis was quoted as saying

> For the Replicator 2, we will not share the way the physical machine is designed or our GUI because we don't think carbon-copy cloning is acceptable and carbon-copy clones undermine our ability to pay people to do development (Brown, 2012).

The "cloning" was a reference to TangiBot, a (legal) direct copy of the Replicator announced several months earlier to be sold for $1200 (one third less than the Replicator) through manufacturing in China. The designer of the TangiBot sought $500,000 in crowdfunding to launch his company, but the effort failed due to resistance from members of the 3DP and open hardware communities.

Despite this provocation, MakerBot's decision to switch from being a pioneer of open source hardware to a closed source design raised considerable controversy. This included a blistering attack from co-founder Smith, who had been forced out earlier in the year:

> For me, personally, I look at a move to closed source as the ultimate betrayal. … Moving from an open model to a closed model is contrary to everything that I stand for, and as a co-founder of MakerBot Industries, it makes me ashamed to have my name associated with it (Smith, 2012).

In a subsequent blog posting, Pettis questioned the viability of the open hardware model for larger companies:

> I wish there were more examples of large, successful open hardware companies. … There are no models or companies that I know of that have more than 150 employees that are more open. … We are experimenting so that we can be as open as possible and still have a business at the end of the day. … I don't plan on letting the vulnerabilities of being open hardware destroy what we've created. …
>
> This isn't the first change we've made to become more of a professional business, and it won't be our last (Pettis, 2012).

Meanwhile, after its acquisition by Stratasys in 2013, MakerBot also benefitted from its parent company's extensive patent portfolio. After it announced three new printers in early 2014, MakerBot published on its website a list of five patents that it asserted covered its five most recent printers: four Stratasys utility patents and one MakerBot design patent (Table 6). One Stratasys patent (6,004,124) was among four listed in a patent infringement lawsuit filed in November 2013 by Stratasys against Afinia, the importer of a low-cost Chinese FDM printer that competed with MakerBot's products (cf. Weinberg, 2013).

Insert Table 6 here

5.2 Software: From Open Source to Proprietary

Over its four-year independent existence, MakerBot evolved its software strategy — as with its hardware design, from a mostly open to a mostly closed strategy (Table 7).

Insert Table 7 here

Its first printer, the Cupcake CNC, used both existing and new open source software for modeling and design. This included Sanguino, an open hardware fork of the Arduino project by Smith originally developed for the RepRap hardware, that used Arduino's open source software libraries for communicating between the computer and the Sanguino microcontroller board. Smith and Mayer incorporated the Arduino software in ReplicatorG, a new open source software project that was the driver for CupCake (and later Thing-O-Matic) printers. The company also used skeinforge, an open source program popular with RepRap users that converted 3D designs into layers that could be printed.

With the 2012 release of its first Replicator printer, the company stopped supporting these two OSS projects, supplanting them with its new MakerWare software. The proprietary MakerWare software addressed two issues. First, it allowed MakerBot to correct some of the problems the earlier open source software had rendering designs, thus improving output quality. Second, the new software simplified the process of producing output, improving ease of use.

While MakerBot continued to recommend open source modeling applications, the company made ongoing improvements in its MakerWare software. Unlike earlier open source software, these improvements were not available to open source hobbyists (e.g. members of the RepRap Project) or to proprietary rivals. At an open hardware conference in 2012, Pettis justified its newly proprietary software strategy to maintain a competitive advantage in ease of use:

> We're also not sharing the GUI of MakerBot MakerWare, which is the software that runs it. That's just because we want to have a chance to control the look and the feel and the experience of the user. And these things are really valuable to people who wanna clone us and just make, like, carbon-copy clones, and we're not…and we're not into that. But, it's still hackable, still modifiable (Ragan, 2012).

6. Creating and Leveraging Thingiverse

The Thingiverse community had a consistent policy of openness with free downloadable content. The shift of MakerBot to closed hardware eliminated the value of Thingiverse to hackers sharing modified printer designs — as well as rival printer makers — but value of other open content to ordinary consumers remained unchanged.

6.1 Launching the Community

Before MakerBot, Smith and Pettis started Thingiverse in October 2008 to encourage open sharing of digital designs for physical products, complementary goods that would make 3D printers more valuable. As Smith explained in his announcement on the official RepRap blog:

> One of the most frequent questions I get after people understand what a RepRap does, is a variant of either 'Why do you need a machine like this?' or 'What do you make once you have one?'. Well, Thingiverse.com is an answer to that. This is no ordinary object sharing website. Thingiverse.com is a home for all your digital designs. If you can represent a physical object digitally, then we want it on Thingiverse. (Smith, 2008).

As Pettis explained in a 2010 interview

> We built Thingiverse because we needed a place to share our designs so we wouldn't lose them and so our friends could make what we had made and then modify those designs and make them better. The community is amazing and supportive, and it's also a lot of fun. There is no other place that you can share a design for a physical thing and people around the world will make their own copies within minutes … It's that kind of sharing magic that makes Thingiverse the closest thing to teleportation that we've got in this solar system. (Peels, 2010).

While initial uploads were primarily vector drawings for 2D laser cutters, the user-generated content rapidly expanded to include 3D models, electronics, and designs, in a range of 2D and 3D object file formats. Content created by an individual "object designer" was shared freely for other community members to download. This community created the first open repository for digital 3D designs. Its design files were free, but the printers were not — following a common slogan among open source hardware businesses: bits are free, atoms cost money.

Because existing 3D content sites were selling designs, the Thingiverse rules were intentionally designed to encourage sharing and thus increase the value of using the open

RepRap hardware (Smith, 2011). This included using the Creative Commons and open source software licenses utilized by RepRap and other open source hardware and software projects, to encourage free revealing and reduce the friction of transaction costs (cf. Harhoff et al., 2003; Balka et al., 2009).

The MakerBot founders used an unusually open community strategy in not selling or directly monetizing any of the designs.[12] In comparison, both the Shapeways and Materialise service bureaus created online communities to sell user-generated content that is printed on demand — as did 3D Systems which acquired an industrial service bureau and used it to launch its consumer-facing Cubify service bureau (Table 8). Only Ultimaker (a direct competitor) emulated MakerBot in creating a community to enable the free use and sharing of designs.

Insert Table 8 here

6.2 Structuring Community Participation

In its first five years, the community attracted more than 100,000 3D designs donated by community members. Reasons for this success include pent-up interest in 3DP, global online availability, and its first mover status as an open repository. However, a key aspect of the success of Thingiverse was due to deliberate choices to promote sharing, including reducing participation barriers, motivating contributions and enabling cumulative innovation (cf. Murray & O'Mahony, 2007; West & O'Mahony, 2008).

While rights to donated designs rested with the designer, Thingiverse encouraged contributors to utilize one of the well-known Creative Commons licenses. Most of these licenses allowed other community members to create derivative works. One popular license (Creative Commons - Attribution - Share Alike) required (as with the open source GPL license) that required those making modifications must share back their changes with other community members. This approach facilitated learning and modification, and served to bind the community of users further through nurturing reciprocity among designers. Developing such norms of reciprocity proved an open factor in motivating contributions to free software communities (cf. O'Mahony, 2003).

Another key institutional choice by the community's founders was to emphasize attribution of design works, providing recognition for designers. Even after MakerBot shifted from open to closed hardware — and moved to assert tighter control over the operation of the Thingiverse website — Pettis emphasized the company's commitment to designer attribution: "The legal terms of use are there to keep Thingiverse legit and protected, not to take away attribution. We know attribution is critical in a community of sharing" (Pettis, 2012).

Attribution facilitates the growth of the community. Thingiverse has grown and evolved into much more than an Open Source and Innovation Sharing platform, but also into the biggest 3D learning community in the digital world (Baichtal, 2008). With more than 100,000 designs and more than 21 million downloads by June 2013, Thingiverse experienced an "explosion of uploaded and published 3D designs" (Howard, 2013), fulfilling its founders' vision of creating a universe of things. At the end of 2013, the most downloaded objects included decorative objects, toys, small useful objects (such as iPhone cases), and component designs (such as circuit boards or robot arms) intended for other makers.

[12] Over time, MakerBot made its brand more prominent, changing the official name to "MakerBot Thingiverse" and requiring a free MakerBot account to log onto the Thingiverse site.

6.3 Benefits to MakerBot

MakerBot focused on two distinct user audiences. One were the makers who — embracing the open hardware ethos — assembled (and modified) MakerBot kits, using them to print physical objects. The others were fabbers (fabricators) who use code (rather than manual drawing) to describe designs. Most of the fabbers have their attention to the procedural designs, and release their design files in the form of openSCAD files, which are intended to facilitate learning and feedback. In an interview, hobbyist design engineer Syvvich described the function of openSCAD as follows:

> Where you don't design the parts, but you write software and it draws them, which is very cool because you can give various characteristics and every time you need a different gear, you just change the software for your parameters, so the 3D printed clock is one big computer program-a great way to work.

Syvvich is a typical hobbyist whose interest is primarily about using code to express design, but seldom 3D prints his designs. The differences between fabbers and makers was starkly illustrated by the differences in their reaction to MakerBot's decision with the Replicator 2 to shift to a closed (i.e. proprietary) hardware design. Steeped in the ethos of open source software, many of the makers criticized the shift away from open IP policies. Makers who are also fabbers are a minority, although some pulled their designs from Thingiverse to protest MakerBot's new IP strategy.

In contrast to the makers, fabbers are more sympathetic and welcome the trade-off between having a better set of tools for design and the tools becoming closed source, as this Thingiverse community member wrote:

> As a professional graphic artist and computer animator, if I was required to use only open-source software and tools to keep a "Fully-Open title" I would go insane. I would be anchored to the sophistication of the tools and I can tell you, while they are excellent tools and are getting better all the time there is a lot of proprietary technology that is nearly essential to functioning in this industry.… Most people who use 3d printers professionally couldn't care less how it works but THAT it works and right now, the challenges of staying "Open" and being competitive in the marketplace are unimaginably difficult for this [open source hardware] business model. [13]

The segmentation of the installed base of Thingiverse users underlines the challenges of mixing open and closed strategies for hardware, software and content, dividing the opinions of contributors, users and investors. In response to the maker community claiming he had violated the GPL by closed sourcing the hardware, Pettis wrote

> It's important to me that we are not violating the licenses of the software. In regards to VC funds, MakerBot does have a duty to do its best to create value for its shareholders, that's part of startup life. But it's not just the VCs, angel, and seed investors, it's also the employees of MakerBot that get value from the company. I'll be the first to say that hardware, open source, and investment are a messy bunch of ingredients to stir up, but we're going to do our best to make it work (Pettis, 2012).

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[13] Comment appended to Pettis (2012) by user Erik J. Durwood II, September 23, 2012.

While the closed approach deterred contributions to the software and firmware that MakerBot used for its printers, it appears to have had limited impact on Thingiverse. Most of the design activities and the sharing of design files remain unaffected, as design files in the Thingiverse are primarily code base subject to the protection of copyright. The attribution system works with fabbers as in the way meritocracy works in other open source software communities.

MakerBot also increased its branding influence over Thingiverse. In 2011, it successfully registered a US service mark for Thiniverse, and in 2014 was granted a US trademark for a Thingiverse mobile app. In 2012, the Thingiverse home page was modified to say a "a MakerBot Industries website". In 2013, the website was rebranded "MakerBot Thingiverse," and users were allowed to log on using either a Thingiverse or MakerBot account, but after January 2014 the site required new users to create a MakerBot account.

Thingiverse still remains as the largest repository for 3D designs, with copyright and attribution used to bind user commitment to ongoing sharing and modification of each others' designs. Thingiverse forms an important bridge for the transition between the digital to the physical worlds, and with freely available designs induces not only an increase in sales of 3D printers, but also the growth of materials. It also remains an online platform for open design, despite the seeming divergence with MakerBot's IP strategy with its shift from open to closed design.

7. Discussion

This case study of MakerBot is one of the first studies of firm strategies for profiting from open hardware designs. Such studies are numerous for open source software, but previous studies of open hardware have emphasized community rather than firm success.

As a startup firm, MakerBot quickly led the consumer 3D printing market in market share and market value. MakerBot delivered a systemic innovation by utilizing a three-way value network that linked existing (externally supplied) open source content generation tools, the Thingiverse open content community that it sponsored, and a combined open source hardware/software printing system that it sold as the initial MakerBot 3D printer models. To create barriers to potential rivals, it migrated the latter from an open to proprietary design, while keeping open the remainder of its value proposition.

Here we summarize the complementarity of MakerBot's selective openness strategies, and offer more general theoretical predictions for other firms utilizing selective openness to gain competitive advantage. We conclude with a discussion of limitations and future research.

7.1 MakerBot's Complementarity of Openness

This study points to what we term the *complementarity of openness* — how openness supports a firm's proprietary strategy and vice versa. We believe this applies both to firms making tangible and intangible products.

The most oft-studied use of the open source model has been for software, which has been both used by independent communities and by entrepreneurial firms that leverage these communities and sponsor their own communities (Dahlander & Magnusson, 2006; Gruber & Henkel, 2006; West & O'Mahony, 2008). However, Raasch (2011; Raasch et al, 2009; Balka et al, 2010) noted the paucity of examples for this approach being viable for supporting hardware, in part because the costs required for designing and producing tangible goods have to be borne by a firm. Their studies show how open hardware communities rely on a symbiotic collaboration with one (and probably only one) firm, suggesting that communities depend on the ability of the sponsoring firm to develop a viable long-term business model.

The MakerBot case allows us to extend knowledge of firm's strategic use of openness in general, and the complementarities of openness in particular. MakerBot's founders used a range of evolving open community strategies to create value while increasing its ability to capture value. Much like open source software companies, MakerBot launched its first products by building upon the freely-available open source hardware designs, and also openly shared the designs for its initial products. However, unlike OSS companies compelled to share designs by free software licenses, MakerBot stopped sharing its hardware designs to build barriers to imitation and win venture investment[14]. The company's CEO asserted that open hardware companies would be unable to grow if they kept an open IP strategy, raising questions as to whether firms can provide long-term sponsorship of open hardware communities the way they have done for OSS communities.

In its software strategy, MakerBot more closely resembled a market-leading proprietary software company (cf. West, 2003). It leveraged open source software when convenient, and even launched an OSS project of its own, but abandoned both when it conflicted with its goals of using proprietary advantage in software ease of use and performance as a barrier to imitation. While once-proprietary firms embrace hybrid strategies of selective openness by "opening parts" (West, 2003), MakerBot took the opposite route — in effect, "closing parts".

However, even after its 2013 acquisition the company continued to sponsor Thingiverse as an open community for user generated content. The firm allowed (and encouraged) MakerBot customers and other users to freely share their digital designs with little or no restrictions, for use with MakerBot and other 3D printers, as these designs created complementary value for the firm's (now proprietary) products.

This pattern thus suggests a complementarity of openness, between the open and proprietary elements of a firm's strategy. It's difficult to support a firm's operations with a fully open offering; this is particularly true for goods with non-zero replication costs (cf. Raasch et al, 2009). Conversely, openness increases the value of the non-open part of a firm's value proposition (West, 2003). With information goods, firms have profited by creating complex offerings (such as software systems or service-based business models) that are a mixture of tightly linked open and proprietary parts (West & Gallagher, 2006).

In the MakerBot case, the complementary offerings are separate and less tightly coupled: the MakerBot printers and Thingiverse content have independent (but complementary) value, because the printer can be used to print its owner's unique designs and the content can be printed on other printers. With both offerings, the three founders started with free revealing of their fully open offerings, in large part due to an ideology of openness that was derived from that of open source software (cf. Dedrick & West, 2008; Henkel, 2009). Under threat of imitation, they largely eliminated the openness of their hardware to deter imitative entry, but largely retained the openness of their complementary content (cf. van Burg et al, 2014).

The founders of Thingiverse used an open strategy to attract contributors. As with other content communities (and two-sided markets more generally), the large supply of content on the site provide network effects that fuel a positive-feedback loop of new contributors and new

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14 MakerBot's failure to share its designs — despite the use of the GPL "copyleft" license by the RepRap community — prompted questions about the efficacy of such licenses for hardware, and efforts to create new licenses that would be enforceable for hardware (Gabriella 2013).

content (cf. Asvanund et al, 2004). The Thingiverse open content was originally intended to support open source RepRap printers, but soon added value to MakerBot's printer designs; the open content was complementary (and thus added value) to both open (RepRap, early MakerBot) and proprietary (later MakerBot) hardware. While the open content thus created value for both open and proprietary strategies, only the latter provided for enough value capture to fuel the firm's growth ambitions.

MakerBot used the open components to complete the value proposition for customers, while gaining advantage by the rapid evolution of its proprietary product that was loosely coupled (through modular interfaces) to the open components. Such loose coupling allows more rapid, decentralized innovation — as was earlier demonstrated for open source software (MacCormack et al, 2012). At the same time, MakerBot's three-part value creation was enabled by aligning the IP modularity to the technical modularity — so that interactions between the different IP strategies were isolated to the well-defined technical interfaces (as later advocated by Henkel et al, 2013).

7.2 Selective Openness as an Entry Strategy

More generally, MakerBot demonstrates how openness both enables and limits the entrepreneurial strategies of new firms. The availability of open source technology reduces entry barriers, enabling the formation and market entry of new firms (Gruber & Henkel, 2006); such efforts correspond to the bricolage used by new firms to gain competencies despite limited resources (Baker et al, 2003). As with many open source software companies (and open hardware companies studied by Raasch et al, 2009, Bock et al, 2014 and others), MakerBot used the availability of open source technology to launch its products — in this case leveraging both open hardware and open software. Two of the three founders launched an open content community even before they had a firm, let alone angel or venture funding. While an open community makes it easier for a firm to create value, it makes it harder to capture value (Simcoe, 2006).

Such an external innovation community is an example of a complementary asset as defined by Teece (1986). Assets that are specialized to a particular firm's innovation will create value for that innovation, while those that are generic (and thus more open) will benefit other innovations including (in many cases) the firm's competitors. While firms might prefer to create or negotiate an external supply of more specialized (proprietary) assets, their ability to do so (particularly for a new firm) will be limited by their financial resources (Teece, 1986; Gans & Stern, 2003). New firms both lack the resources to make the investment themselves, and (often) to incentivize third parties in their ecosystem to make such investments (West, 2014).

Given these financial constraints, we would expect that new firms (particularly resource-limited ones) will be more open than established firms with greater resources:

> Proposition 1: For firms that require new complementary assets to commercialize their innovation, new firms will be more willing than established firms to source these assets as generic assets.
>
> Proposition 2: Among new firms that require new complementary assets to commercialize their innovation, their willingness to source these assets as generic assets decreases as the availability of financial capital increases.

While resource availability makes it *possible* to be more proprietary, a certain form of resources makes it *desirable* to be more proprietary. Specifically, professional investors (whether angels, independent venture capitalists or corporate venture capitalists) prefer to invest in firms with high barriers to rivals (e.g., Berkery, 2008). In this case, MakerBot shifted from open to proprietary hardware 13 months after receiving $10 million in series A funding. Considering both the utilitarian and normative explanations, we predict

> Proposition 3: After firms receive venture or other professional investment, their openness will decrease more rapidly than those that do not receive such investment.

7.3 Closing Parts

While earlier firms have also pursued a partly open strategy (e.g. Henkel, 2006; Shah, 2006), MakerBot was unusual both in the degree of its shift from an open to proprietary product strategy, and how rapidly it executed that shift. However, any firm that chooses to open parts of a complex system (West, 2003) must choose what parts to make (or source) as open technology and which part will be proprietary technologies. In MakerBot's case, even after one round of venture investment, it couldn't replace all of its open technology with purely proprietary technologies. This highlights the general question: for a firm "closing parts", which parts should be made proprietary?

Differing parts of a systemic innovation will be more important for competitive advantage than others. In a complex system, some components are more customer-visible or customer-valued than others (West & Gallagher, 2006). Some parts are not feasible to modify because standardized components create strong scale economies or switching costs (Langlois & Rboertson 1992). The overall system performance may be hampered by components that lag the rest of the system, technologies that Hughes (1987) labels a "reverse salient"; firms choose to improve these components, eliminating the reverse salients to most rapidly improve system performance and thus product sales (Davies 1996; Teece, 2006).

Therefore, we would expect

> Proposition 4: When a firm switches from an open to partly closed strategy, *ceteris paribus,* it will make proprietary those parts most important to its value proposition.

Finally, when firms work with an external community, for a variety of reasons they may find certain types of contributions of value easier to source from communities than others. At one extreme, some contributions are so easy to source from external communities — in cases such as peer-to-peer tech support — that they may not even require an organization to receive or mediate the provision of the value (Lakhani & von Hippel, 2003). At the other extreme, technical complexity may make it difficult for external contributors to understand how to contribute or be willing to make the effort to contribute (West & O'Mahony, 2008). Systems with low technical modularity will be harder for outsiders to understand (and contribute to) than those with high modularity (MacCormack et al, 2006). Finally, some forms of knowledge or other external innovations are more difficult for a firm to acquire and utilize — such as highly tacit or context-specific knowledge (von Hippel, 1994) — and thus we would expect such innovations would be less likely to be externally sourced. At the same time, firms are more likely to gain competitive advantage by maintaining trade secrets around tacit or other complex parts that are difficult for rivals to imitation (Cohen et al, 2000).

Overall, we predict

> Proposition 5: Firms are most likely to make proprietary those components that are most difficult to obtain from external contributors, or most difficult to assimilate when provided by external sources.

7.4 Limitations and Future Research

Our research was limited to a single case study within an emerging sector within the 3D printing industry. Although our choice of the research site was an extreme exemplar, it had a set of unique characteristics, including the importance of open source hardware and software in the formative stage of MarketBot, and the contributions and inputs from various open source user groups and communities to the making and the success of MarketBot at a later stage. Nevertheless, the case provides a rich set of insights that can be generalizable to different settings. First, it shows how openness in content can afford a switch from an open to a proprietary strategy in hardware. This contributes to our understanding of how an open source company can grow its open content to support a proprietary model to compete with rival firms.

Next, our study identified only a few consumer 3DP manufacturers that operated their own content communities as a source of complementary value. Yet, we were unable to identify a competing 3DP manufacturer that went from open to closed: instead, the general pattern seems to be that open firms stay open and (as with the industrial makers) closed firms stay closed. Thus, further research is needed to understand more generally how hardware producers choose an open or closed strategy, the antecedents and consequences of such choices and — in particular — the relationship of those decisions to their complementary asset portfolio. More generally, we endorse the call of Raasch et al (2009) for more research on how openness strategies developed from open source software do (or do not) apply to companies producing tangible goods.

Third, the conditions prompting the trajectory from open to closed can be materially different from the opposite trajectory from closed to open. Future research can compare and contrast these diametrically opposite trajectories, and notably their impacts on user communities and the growth and success of enterprises and businesses.

The nature of competition and competitive advantage will change as the industry grows, matures and consolidates. Therefore, many openness strategies that worked for firm entry or early in the industry life cycle will become obsolete if consumers demand low cost (driving commoditization), differentiation (increasing the value of R&D) or interoperability (strengthening network effects and thus the value of market share or interfirm product standardization).

Finally, with 3D printers still relatively rare, it is too early to study the full impact of the digital representations upon tangible consumer goods. We expect that such representations will have a different impact on consumer use value (and industrial organization) than would information goods (such as entertainment or software) that can be consumed digitally. We suggest that the adoption (and impact) of copy machines and (2D) color printers on printed pages might suggest analogs for studying how 3D printing will change the value created (and captured) by manufacturing 3-D objects. Researchers could also use the 2D analogs to help identify niches both where 3D printed digital content will potentially find the earliest adoption, and also those niches that are most resistant to disruption and displacement by this new technology.

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10. Tables

Table 1: Comparison of Industrial and Consumer Markets

	Industrial	Consumer
First System Sold	1987	2008
Units Sold (through 2013)	66,700	140,425
Unit Sales (2013)	9,832	72,503
Average Unit Price (2013)	$73,800	$1,208
Systems Revenues (2013)	$976 million	$88 million

Source: Estimates as published in *Wohlers Report* (2014)

Table 2: Additive manufacturing technologies and patents

Process	First Granted US Patent (Priority Date)	Key Inventor (Employer)	Feedstock
Stereolithography (SLA)	4,575,330 (1984)	Chuck Hill (UVP, later **3D Systems**)	Liquid plastic
Laminated Object Modeling (LOM)†	4,752,352 (1986)	Michael Feygin (later **Helisys**)	Paper
Selective Laser Sintering (SLS)	4,863,539 (1986)	Carl Deckard (U. Texas)	Plastic or metal powder
Solid Ground Curing (SGC)	4,961,154 (1986)	Itzchak Pomerantz (SciTex, later **Cubital**)	Liquid plastic
Fused Deposition Modeling (FDM)††	5,121,329 (1989)	Scott Crump (**Stratasys**)	Continuous spool of plastic (later metal)
Electron Beam Melting (EBM)	5,786,562 (1993)	Ralf Larson (Larson Brothers)	Metal powder
Inkjet-based approaches			
Three-Dimensional Printing (3DP)†††	5,204,055 (1989)	Michael Cima, Emanuel Sachs (MIT)	Liquid plastic or plastic-metal
Inkjet Printing (IJP)	5,506,607 (1991)	Royden Sanders Jr. (later **Solidscape**)	Wax
PolyJet	6,259,962 (1999)	Hanan Gothait (**Objet**)	Liquid plastic

† Trademark of Helisys

†† Trademark of Stratasys; competitors use the term Fused Filament Fabrication (FFF)

††† Trademark sought by MIT, later abandoned

Additive manufacturing equipment producers listed in **bold**

Sources: Key additive manufacturing inventors, universities and firms were identified from technical publications. For this list, Google Patents was used to search for all US granted patents prior to 2000.

Table 3: Key 3D Printing Companies

Founded	Company	Spinoff Parent	HQ	Printing Process	First System	Initial Target	Exit
1985	**Helisys (née Hydronetics)**		Los Angeles	**LOM**	ca. 1990	Industrial	1996: IPO 2000: out of business
1986	**3D Systems**	UVP	Los Angeles	**SLA**	1987	Industrial	1987: IPO (Vancouver)
1986	**Cubital, Ltd.**	Scitex	Israel	**SGC**	1991	Industrial	2000: out of business
1987	**DTM Corporation**	UT Austin	Austin	**SLS**	1992	Industrial	2001: Acquired by 3D Systems
1989	EOS GmbH		Germany	SLA,SLS	1994	Industrial	n/a
1989	**Stratasys**		Minneapolis	**FDM**	1992	Industrial	1994: IPO (NASDAQ)
1990	Materialise NV	KU Leuven	Belgium	*Service Bureau*	-	Industrial	2014: IPO (NASDAQ)
1993	**Solidscape (née Sanders Prototype)**		New Hampshire	**IJP**	1994	Commercial	2011: Acquired by Stratasys
1994	Z Corp		Boston	3DP	1997	Industrial	2012: Acquired by 3D Systems
1998	**Objet**		Israel	**PolyJet**	2001	Industrial	2012: Merged with Stratasys
1996†	ExOne	Extrude Hone	Pittsburgh	3DP	1999	Industrial	2013: IPO (NASDAQ)
1997	Arcam	Chalmers University	Sweden	EBM*	2002	Industrial	2000: IPO (Nordic Growth Market)
2007	Shapeways	Phillips	Netherlands	*Service Bureau*	-	Commercial	n/a
2009	Afinia		Minneapolis	FDM	2012	Consumer	n/a
2009	MakerBot		New York City	FDM	2009	Consumer	2013: Acquired by Stratasys
2011	RepRap Professional	RepRap Project	UK	FDM	2011	Consumer	n/a
2011	Ultimaker		Netherlands	FDM	2011	Consumer	n/a
2011	Formlabs		Boston	SLA	2012	Consumer	n/a

Processes invented by a company founder or employee are listed in **bold**
* Exclusive patent license from inventor
† Parent company began 3D printing in 1996, spun off in 2005
†† Spun off as independent company in 2010

Table 4: Potential barriers to consumer adoption of 3D printing

Category	Attributes
Printer performance	Speed, quality, output size, output durability
Cost	Initial cost, cost of consumables
Computer performance	CPU cycles, RAM, hard disk
Application software	Computer Aided Design (CAD) applications
Ease of use	Graphical interfaces, hardware operation, integration
Content (digital designs)	Self-designed, standardized components, community donated content

Table 5: MakerBot product history, 2009-2013

Date	Product	Price§	Design License	Build Volume	Min. Layer Resolution	Printing Material
March 2009	Cupcake CNC	$750†	GNU GPL	100 x 100 x 150 mm	n.s.	PLA (Polylactic Acid)
Sept. 2010	Thing-O-Matic	$1,300† $2,500	GNU GPL	110 x 110 x 120 mm	0.25 mm	PLA
Jan. 2012	Replicator	$1,750	Creative Commons	225 x 145 x 150 mm	0.20 mm	PLA or Acrylonitrile Butadiene Styrene (ABS)
Sept. 2012	Replicator 2	$2,200	*trade secret*	285 x 153 x 155 mm	0.10 mm	PLA
Jan. 2013	Replicator 2X	$2,800	*trade secret*	246 x 163 x 155 mm	0.10 mm	PLA or ABS
Jan. 2014	Replicator Mini*	$1,380	*trade secret*	100 x 100 x 125 mm	0.20 mm	PLA
Jan. 2014	Replicator (5^{th} generation)*	$2,900	*trade secret*	252 x 199 x 150 mm	0.10 mm	PLA
Jan. 2014	Replicator Z18*	$6,500	*trade secret*	305 x 305 x 457 mm	0.10 mm	PLA

Source: MakerBot website, news reports
§ Base model at time of introduction
† Kit form
* Introduced after being acquired by Stratasys

Table 6: Self-declared patents applicable to MakerBot products

Patent	Priority Date	Issue Date	Assignee	Applicable Products
6,004,124	1/26/98	12/21/99	Stratasys	Replicator 2,2X,Mini, Z18, 5th gen
6,722,872	6/23/99	4/20/04	Stratasys	Replicator Z18
6,749,414	4/30/01	6/15/04	Stratasys	Replicator 2X
7,384,255	7/1/05	6/10/08	Stratasys	Replicator 2,2X,Mini, Z18, 5th gen
D677,723	9/18/12	3/12/13	MakerBot	Replicator 2,2X

Source: www.MakerBot.com/patents; also US PTO

Table 7: Commercial and open source software for consumer 3D printing

Category	Input	Output	Open Source Examples	Commercial Examples
Modeler	Drawing file (.dwg, .dxf), wavefront file (.obj)	Stereo lithography file (.STL)	Blender, OpenSCAD, Art of Illusion	Google Sketchup†, Autodesk 123D Design†
Slicer	STL file	Layer definition (G-Code) file	skeinforge, Slic3r	**MakerWare,** KISSlicer†
Printer Driver	G-Code file	Printer commands	ReplicatorG	**MakerWare**
Controller Driver Library	*Programmer APIs*	*Low-level serial output*	Arduino, Sanguino	

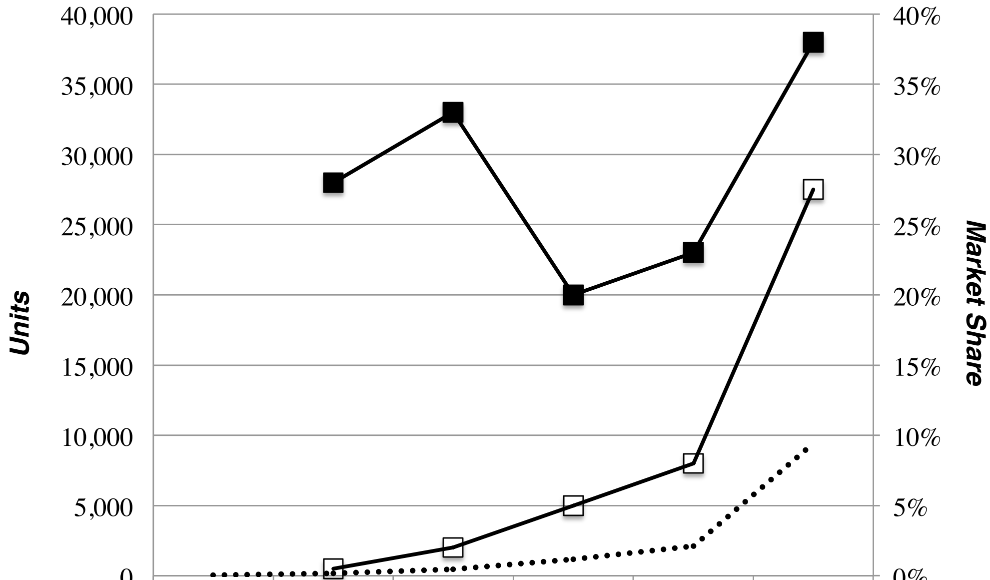
Source: project websites, *Make* (2013) † Entry level version available free

Table 8: Online content communities sponsored by 3D printing companies

Community	Sponsor	Related Sponsor Revenues	Launch Date	Free Designs	Designs for Sale	Printed Versions for Sale
Thingiverse	MakerBot	consumer 3D printers	2008	X		
Shapeways	Shapeways	consumer service bureau	2009		X	X
i.materialise	Materialise	industrial service bureau	2010		X	X
Cubify†	3D Systems	consumer service bureau	2012		X	X
YouMagine	Ultimaker	consumer 3D printers	2013	X		

† Launched based on its 2011 acquisition of the Quickparts industrial service bureau.

Figure 1: MakerBot and Thingiverse success



	2008	2009	2010	2011	2012	2013
Thingiverse New Objects	31	159	453	1,181	2,127	9,436
MakerBot Printers (Unit Sales)		500	2,000	5,000	8,000	27,500
MakerBot Printers (Market Share)		28%	33%	20%	23%	38%