3-21-2017

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Pearce, JM 2017 Emerging Business Models for Open Source Hardware. *Journal of Open Hardware,* 1(1): 2, pp. 1–14, DOI: https://doi.org/10.5334/joh.4

ISSUES IN OPEN HARDWARE

Emerging Business Models for Open Source Hardware

Joshua M. Pearce*,†

The rise of Free and Open Source models for software development has catalyzed the growth of Free and Open Source hardware (also known as "Libre Hardware"). Libre Hardware is gaining significant traction in the scientific hardware community, where there is evidence that open development creates both technically superior and far less expensive scientific equipment than proprietary models. In this article, the evidence is reviewed and a collection of examples of business models is developed to service scientists who have the option to manufacture their own equipment using Open Source designs. Profitable Libre Hardware business models are reviewed, which includes kit, specialty component, and calibration suppliers for makers. The results indicate that Libre Hardware businesses should target technically sophisticated customers first and, as usability matures, target expanded markets of conventional consumers.

Keywords: Open Source; Open Source Hardware; Libre Hardware; Business Models; Innovation

1. Can You Make a Business of Open Source Hardware?

Conventional business models for hardware sales normally involve creating artificial scarcity for a product by obtaining a monopoly over it (Demsetz, 1973; McGaughey, 2002; Smith, 2007; May, 2013). This is accomplished by either protecting the intellectual property (IP) (Teece, 2000) related to the product as a trade secret or with a patent, the latter of which provides an exclusive right to make and sell the product for 20 years in the U.S. and other members of the World Intellectual Property Organization (WIPO). This provides the firm with a monopoly over the product (Boldrin, 2005; Boldrin and Levine, 2008; 2009). Conventional business wisdom states that "failure to implement appropriate legal measures [e.g. patents] can prevent firms from fully realizing the benefits of the other resources they control" (Bagley, 2008). After obtaining an IP monopoly, a firm can extract fees in, for example, the forms of royalties to use the IP or simply raising the selling price of the monopolized product (McGaughey, 2002). These types of business models are well known and most corporations employ them in a wide range of hardware industries (e.g. aerospace, automotive, electronics, household appliances) and they are very common in the software industry in the U.S. as well (USPTO, 2013).

Interestingly, recent innovations in the software industry have favored an alternative model – that is, liberating otherwise restrictive IP to the global community as Free and Open Source Software (FOSS) (Lerner and Triole, 2000; Lakhani and Von Hippel, 2003; Bonaccorsi and Rossi, 2003; Vetter, 2009). There is a large body of literature on the benefits of FOSS over established development models (Deek and McHugh, 2008; DiBona et al. 1999) which describes why firms would choose to liberate software-related IP and join collaborative and distributed development. The FOSS community has demonstrated through many successful software projects that, by facilitating participation in projects with little to no startup costs, meaningful contributions from the community can be made (Raymond, 1999; Lakhani and Von Hippel, 2003; Weber, 2004). Large-scale collaborations result in superior design with lower associated costs due to the continuous improvement, which leads more robust and innovative solutions to technical problems (Raymond, 1999; Soderberg, 2008). FOSS has been shown to be more reliable and relevant to users and this is not surprising as many FOSS users are co-developers (Kogut and Metiu, 2001). FOSS has become so prominent in the software industry that it is changing the trajectory of software developers' careers (Riehle, 2015) and dominating major areas of computing. For instance, Android, an Open Source-based operating system for smart phones dominated the market with an 82.8% share in the second quarter of 2015 (IDC, 2016) and 97% of the world's supercomputers operate on GNU/Linux (Vaughan-Nichols, 2014). Major Internet firms use and develop FOSS including, for example, Google (Google, 2015), Amazon (Clark, 2014), and Facebook (Facebook, 2016). The success of FOSS has created an alternative to expensive and proprietary systems by allowing for reduced research and development costs as well as more flexible design (Mockus, Fielding, Herbsleb, 2002).

As FOSS has proven successful there have been efforts to create businesses with Open Source Hardware (OSHW). OSHW is hardware whose design is made publicly

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available so that anyone can study, modify, manufacture, distribute, and sell the design or pieces of hardware based on that design (OSHWA, 2016). For simplicity for the remainder of this article "Libre Hardware" will be used as a shorthand notation for OSHW in order to emphasize development founded on values of freedom as opposed to price. Originally FOSS community members believed that Libre Hardware was challenging because of the nature of the design that was necessary to build physical artifacts (Stallman, 1999), however, with advancements in digital manufacturing technology these views have changed (Stallman, 2015). There are several examples of existing vibrant Libre Hardware communities (Gibb, 2014) such as the 3D printing community around the self-replicating rapid protoyper (RepRap)[1] 3D printer family (Jones, Haufe and Sells, 2001; Sells et al., 2009; Bowyer, 2014). RepRap technology has been attributed with radically reducing the costs of 3D printing and generating the entire desktop 3D printing market, which spawned dozens of new companies (Rundle, 2014; Molitch-Hou, 2016). Open Source innovation in both software and hardware has the potential to include more participants than proprietary or closed-source innovation within firms, and it is less encumbered by IP issues, providing a competitive advantage (Chesbrough, 2003; Huizingh, 2011; Yu & Hang, 2011). Thus, the trajectories of improvements and innovation are steeper (Foss and Pedersen, 2004) than they are for traditional manufacturing technologies, which provides a second competitive advantage. Improvements are continuous as new designs are published on a regular basis. Repositories for 3D objects have users, for instance, who continually post new designs. At the moment, most designs (for printed objects) are hard to copyright, and copyright laws can be bypassed through the introduction of small changes in the overall design (Bradshaw et al., 2010). Copyright is not the appropriate IP strategy for design files on any product that has utility (e.g. patents). Therefore, YouMagine, Stanford 3D Scanning Repository, Github, Repables, Pirate Bay Physibles, Fab Fabbers, Cubehero, Bld3r, Thingiverse, Libre 3D and many other repositories are blossoming (RepRap, 2016). The number of libre designs have been shown to be growing at an exponential rate (Wittbrodt et al., 2013) and a single repository now holds more than 1 million designs.

One area where Libre Hardware is gaining significant traction is in the scientific hardware community (Fisher and Gould, 2012; Pearce, 2014). There is substantial evidence that the Open Hardware model creates more flexible and adequate scientific equipment at far less expense than has been developed using proprietary models. In this article, the evidence for this will be reviewed to describe a collection of examples of business models to service experimental scientists who have the option to manufacture their own scientific hardware using Free and Open Source designs. To discuss business models to supply this novel type of expert consumer, profitable Libre Hardware-based products in the sciences will be reviewed. These business models will be generalized to other types of customers who are capable of distributed digital fabrication of libre designs to meet their own needs. Finally, conclusions will be drawn about businesses that must compete not only with other producers for customers but also with the customers themselves.

2. Background: The Rise of Free and Open Source Scientific Hardware

Scientists building on the success of the Arduino Open Source prototyping platform and the RepRap 3D printing[2] communities have begun a new phase of distributed digital fabrication of low-cost scientific equipment (Pearce, 2012; Pearce, 2014; Baden, et al., 2015). Free and Open Science Hardware projects span a wide range of scientific disciplines with an incredible variety of tools, including: colorimeters (Anzalone et al., 2013a), photometric systems for enzymatic nitrate quantification (Wittbrodt, et al., 2015), nephelometers (Wijnen et al. 2014a) and turbidimeters (Kelly et al., 2014), liquid auto-samplers (Carvalho and Eyre, 2013), microfluid handlers (Da Costa, et al., 2014), biotechnological and chemical labware (Lucking et al., 2014; Gross et al., 2014; Su et al., 2014), mass spectroscopy equipment (Malonado-Torres et al., 2014; Chiu and Urban, 2015), automated sensing arrays (Wittbrodt, et al. 2014), phasor measurement units (Laverty et al., 2013), syringe pumps (Wijnen et al., 2014b), optics and optical system components (Zhang et al., 2013), DNA nanotechnology lab tools (Damase et al., 2015), outdoor monitoring (Pearce, et al., 2012; Chemin et al., 2014) and compatible components for plasma physics labs (Zwicker et al., 2015) and medical apparatuses like magnetic resonance imaging systems (Hermann et al., 2014).

Collaborative practice of sharing digital designs have reduced the capital costs of such Libre Hardware to an unprecedented 90–99% decrease from the cost of functionally-equivalent proprietary equipment (Pearce, 2014a; Pearce, 2014b). Consider three examples. First, replacing a $2,000 hand-held water quality tester can be done for under $100 if Open Source electronics and 3D printed parts are used (Wijnen, et. al. 2014). The RepRap used for fabricating the water quality tester costs less than $500 (Irwin, et al., 2015). Thus, even if only a single water quality tester is printed, the costs of the open source 3D printing manufacturing technology are more than justified for the scientist. Similarly, the majority of mechanical fixtures for optics labs in physics research and education can be replicated from common 3D printed plastic. A $15,000 optics lab can be reduced to a $500 3D print job (Zhang, et al., 2013) on a sub-$500 3D printer. Such savings can scale to many research laboratories once the initial designs are produced and licensed with Open Hardware licenses. For example, biologists, chemists, and biochemists can print a syringe pump and automate it for under $100 replacing traditional syringe pumps which range from $250 for low-end pumps to over $5000 for sophisticated ones (Wijnen, et al., 2014). The Open Source syringe pump library can facilitate matching a scientists needs throughout this spectrum of pump sophistication. As each of the designs can be replicated for little more than the cost of materials and modest electricity to run 3D printers, the economic value for the scientific community is substantial (Pearce, 2013; Pearce, 2015). In this particular case within a month of the release of the Open Source syringe pump designs the scientific community saved over $1 million in high-end syringe pump purchases (Pearce, 2014c). This investment could provide return on investments (ROIs) enjoyed by the scientists to their funders, such as the National Institutes of Health (NIH) and the National Science Foundation (NSF) ranging from 100s to 1,000s of percent after only a few months of release (Pearce, 2016a). These agencies have the option to put strong incentives in place to better harness this opportunity by having specific CFPs (calls for proposals) for Open Hardware as well as preferential purchasing policy to be set for Free and Open Source solutions when available in quantity and sufficient quality (e.g. precision, accuracy, reproducibility, durability, etc.).

3. Conceptual and Practical Challenges: Customers Capable of Distributed Digital Fabrication to Meet Their Own Needs

As the preceding section made clear, scientists are now turning to Libre Hardware to conduct their experimental science in greater numbers than ever before. However, proprietary hardware maintains a persistent dominance. A careful inspection of the citation years (e.g. ≥2012) in the preceding section should makes it clear that Libre Hardware is a very recent phenomena. There is still considerable inertia in the scientific equipment funding, distribution and purchasing systems that have, thus far, limited Open Hardware to a small number of specialized areas. There are three primary obstructions to gaining domination of mainstream science equipment. First, funding is limited for Open Hardware development. Conventional financiers are both familiar with and prefer patent protection for their investments[3] (Demsetz, 1973; McGaughey, 2002; Smith, 2007; May, 2013). This IP model was made into a piece of legislation by the Bayh–Dole Act in the U.S., which allows inventions of government-funded research to be privatized (Eisenberg, 1996). There is already considerable evidence that this approach slows innovation in some fields such as nanotechnology (Pearce, 2012b). Regardless, this approach is now firmly entrenched in all areas of funding in both private and public sources of equipment research. For example, the National Science Foundation (NSF) recently revised their proposal preparation instructions (NSF, 2016) such that the former category of "publications", which covered peer-reviewed publications, was renamed "products" and expanded to include patents. Although there are examples of government funding for Open Hardware development,[4] there has not been specific programs. Most major equipment grants such as those for the NSF Major Research Instrumentation (MRI) program go towards funding the purchasing of proprietary tools from conventional vendors or specialty equipment development, which is later commercialized as proprietary equipment. Secondly, because of the nature of distributed manufacturing there are nearly no examples of open scientific hardware being included in scientific equipment catalogs from major vendors which makes it difficult for scientists who are not familiar with Open Hardware to consider it when purchasing equipment. Finally and most importantly, established institutions and funding agencies favor purchasing proprietary equipment. Because open hardware costs less, it provides ironically a perverse incentive for universities to avoid it in order to acquire as much overhead as possible. This is made clear by the arbitrary definition of equipment that is capped at $5,000, which clearly penalizes most existing low-cost Open Hardware (Pearce, 2016b). This bias is not in the best interest of science, however, there are also legitimate reasons why most scientists still favor proprietary tools due to long track records and traditional customer service of established suppliers. Many scientists are not comfortable with developing their own equipment and, despite improved performance and lower cost, prefer an out-of-the-box tool with stable channels of technical support. Even these labs, however, may be tempted to save costs by using the distributed manufacturing model for non-critical tools or custom components.

The distributed manufacturing Libre Hardware phenomena has been made possible with the development of inexpensive global communication and a wide variety of projects which operate as platforms, such as the Arduino electronics prototyping project and the RepRap physical fabrication platform. The Arduino platform has been used for many scientific applications including: low-cost UAVs for oceanographic research (Busquets, et al., 2012), behavioral experiments (D'Ausilio, 2012), pressure monitoring (Russell et al., 2012), drop velocity measurements (Fobel, et al., 2013), microscopy (Gualda, et al., 2013), electrophysiology (Newman, et al., 2012), Skinner boxes (Pineño, 2014), and multi-spectral in-vivo optical image acquisition (Sun et al., 2010). In addition, the Ardunio-enabled RepRap has been modified to work as a printed circuit board (PCB) mill (Anzalone, et al., 2015), so that the Arduino main board itself can be fabricated using the RepRap along with a wide range of Open Source circuit designs. It should be pointed out here that Libre Hardware is much more likely than proprietary hardware to be adopted as a platform because it is easier to hack and build upon (Zimmermann, 2014).

The Libre Hardware approach has several advantages for scientists. First, lower costs (in time and money) are enjoyed for direct manufacturing equipment. It is also likely that the price pressure from the Open Source community (Deek and McHugh, 2007) will drive down costs of commercial versions of the equipment, resulting in a decrease in overall research costs. Second, greater flexibility and customized equipment that would be expected to lead to better experiments and faster evolution of science (Pearce, 2014). Rather than being limited to buy only what is commercially available, scientists can create scientific instruments to meet their exact needs and specifications, expanding on Open Hardware design files. The ability to customize research tools is particularly helpful to those on the bleeding edge of science, who need customized never-seen-before equipment. Third, better control over their labs. Open source products are well known to offer a decreased dependency on monopoly suppliers (Bruns, 2000; Kogut and Metiu,

2001) and this benefit can be very valuable to scientists using Libre Hardware. If a scientist has the legal and technical ability to alter the code for hardware and software in their labs, they will never be left with stranded assets such as non-functioning equipment when commercial vendors go out of business, drop a product line, or loose key technical staff. With libre hardware, the equipment, at least, has the potential to evolve rather than being discarded.

Acknowledging these advantages scientists can thus be categorized by their adoption of Libre Hardware into four categories. The first three provide markets for potential Libre Hardware-based businesses. First, some scientific research groups (Type 1) fabricate their own equipment using Libre Hardware designs in-house. Type 1 scientists will be referred to as a 'makers'. Second, some scientific research groups (Type 2) would be willing to pay more for equipment by having someone else fabricate for them. This would include well funded groups, groups on strict timelines, and those who lack appropriate staffing. For example, some scientific research groups, particularly those outside of physics and engineering, might lack the expertise to use Open Source tools to fabricate equipment themselves. Other research groups (Type 3) outsource their experiments to core facilities or businesses, and these organizations could conduct research for a fee. Finally, some research groups (Type 4) would remain with the traditional proprietary suppliers in order to continue to outsource their risk, which is one of the benefits of the traditional model. However, it should be pointed out that the diminished market from the first three groups of scientists may eliminate traditional suppliers, thus removing this option in the future. Businesses are needed to service the Libre Hardware scientific market made up of the first three groups, and the next section will review profitable models such businesses can follow.

4. Open Hardware Business Models to Serve the Scientific Community

A business model describes the rationale of how a firm creates, delivers, and captures economic value (Hedman and Kalling, 2003). The business model is essentially a plan that a company uses to generate value. Companies developing and distributing FOSS can not depend on their control of the source code for their business model, they rely on non-traditional models to provide sources of revenue instead (Krishnamurthy, 2005). In the Open Source context, the definition of business model can be made up of three components: 1) value (i.e. value proposition for customers and the business); 2) revenue (i.e. how the business can earn revenue, the primary focus of most Open Source business model research), and 3) logistics (Mahadevan, 2000). In this section, business models serving different types of scientific users (makers, Open Hardware buyers, and outsourcers) will be discussed to address the larger Libre Hardware community. It should be noted that a single business can use more than one model to generate revenue.

4.1 Business Models to Serve Scientists: Makers (Type 1)

4.1.1. Kit Suppliers

At the present stage of Libre Hardware development the majority of complex scientific hardware can not be fabricated solely by low-cost digital manufacturing tools, such as polymer-based single-material 3D printers. Thus, the equipment demands non-printed parts, which is what the RepRap 3D printer community refers to as "vitamins". For complex equipment, these vitamins may not be readily available or may represent a major time investment to source, thus there is a market for firms to provide all the vitamins for a specific tool in a kit form. For example, a firm could produce kits to fabricate an open tool such as the Arduino-powered OpenQCM, which is a highly-sensitive Open Source microbalance. Kit suppliers can differentiate themselves following the sucessful business example of Adafruit, which is well known for providing high-quality tutorials for building Open Hardware projects (Zimmermann, 2014).

4.1.2. Specialty Component Suppliers

In the maker scientific community there will be customers who still want some level of specialization of their equipment beyond common kit models. Businesses can supply custom parts in materials that are not commonly available for digital fabrication in desktop 3D printers such as Shapeways, which enable scientists to order custom print Open Hardware components in exotic materials such as bronze, porcelain, castable wax, and aluminum (Shapeways, 2016). Although RepRap printers have been developed to print in wax (Pearce, et al., 2016c), steel (Anzalone, et al., 2013b) and aluminum (Nilsiam, et al., 2015), these printers are not yet well refined or widely distributed.

Similarly, vitamin suppliers can provide hard-to-obtain specialty components such as sensors or complex electronics to this type of customer. In their online store, OpenQCM provides not only full kits, but also the relatively uncommon 10MHz Quartz sensors separately for those capable of obtaining and fabricating the QCM Arduino shield and 3D printed components themselves. In addition, as makers favor the so-called Open Hardware vitamins, there is a competitive advantage to offering open versions of mass produced components. For example, OpenBeam is an aluminum extrusion construction system that can be used to make optical rails (Zhang et al., 2013). Even though individual scientists could use the plans to make their own runs, the quantities they would need make it much more likely they would purchase the beams a few at a time from the original supplier, OpenBeam.

4.1.3. Calibration and Validation Services

In order to provide scientists with the assurance that their tools are operating at specification, calibration and validation is often necessary. For example, a calibrated light source from Ocean Optics may be necessary to perform accurate experiments in an Open Source-based optics setup for photoluminescence. Businesses can service the needs of scientists either by shipping calibrated or validated Open Hardware components directly or by accepting hardware built by other scientists for testing. This service is extremely important in the scientific community[5] as it provides researchers with security in the knowledge that their measurements or functionality with a given tool are accurate. This warranty of calibration and validation is well established for proprietary vendors. This advantage lies primarily with the relatively new Libre Hardware field, however there is no technical reason that Open Hardware could not be equally well calibrated and validated. Although there are hundreds of open scientific hardware designs, only a small fraction have been formally validated and an even smaller amount are sold as calibrated units. As soon as the Libre Hardware community begins to offer this service, the cost advantage would help shift some of the scientific market to Libre Hardware. The rate of adoption of Libre Hardware would also be assumed to accelerate with further funding cuts putting financial pressure on both science and medical researchers (Charlton and Andras 2005; Jaffe, 2015; Balch et al., 2015).

4.2 Business Models to Serve Scientists: Open Hardware Buyers (Type 2)

4.2.1 Selling Libre Hardware

This open business model is perhaps the most similar to traditional business models in that the firm fabricates and sells hardware, which happens to have its design fully documented and freely available. Examples in the scientific hardware community include products like OT. One, a $3,000 USD liquid handling robot developed by OpenTrans; or the $649 USD OpenPCR, a PCR machine for DNA detection and extraction. Both of these devices offer a considerable discount to scientists when compared to proprietary versions with comparable functionality. One can sell Libre Hardware either as pre-sales through crowd-funding services, through conventional "brick and mortor" retail stores, or e-shop sales. A good example of how this business model works in practice after the Libre Hardware business is mature can be seen in the success of Aleph Objects, which sells the Lulzbot Open Source software and hardware-based desktop 3D printers (Griffey, 2014). These printers can be used to make a long list of scientific tools themselves including test tube racks, centrifuges, and microscope accessories (Pearce, 2014). The Lulzbot printers are derivatives of earlier RepRap printers: Aleph Objects uses its own 3D printers to fabricate many of the components of their finished product following the RepRap philosophy (Krassenstein, 2015). Although anyone could fabricate a Lulzbot 3D printer using Aleph Objects' plans, the cost and difficulty would likely be more than simply purchasing the device from the supplier. This model can be seen as a commercial enhancement one as customers have some assurance that an Aleph Object printer will work to specification, which is more than what is guaranteed by self-assembly or rival clones. In exchange for the risk of rival copiers undercutting its market, Aleph Object enjoys lower research and development costs and more rapid deployment of products to market because of the feedback from their users (Zimmermann, 2014). The value of this feedback should not be underestimated, as it is common in many, but not all, Libre Hardware projects for substantial contributions or enhancements to be offered with skills and costs that a single company would not be able to afford (Zimmermann, 2014). This includes developers who may not want to work for a company full time, retired engineers, or those who live in other countries. One method to compete against incumbents in the business world, which is well established, is to utilize innovation, with radical innovation being more profitable (Sheremata, 2004). It has also been shown that collaborative expert networks are of crucial importance in achieving a higher degree of novelty in product innovation (Nieto and Santamaria, 2007). Thus, Aleph Objects enjoys the benefits of a free global engineering base that rapidly innovates on their products as part of the RepRap community. It is not surprising that their Lulzbot Taz 5 was the best overall machine in the "Digital Fabrication Shootout" sponsored by Maker Media – beating all of the proprietary desktop 3D printers analyzed in 2015 (Make, 2015). Thus, an open hardware company can compete on quality, warranty, and other conventional business metrics such as customer service and delivery speed.

There are numerous examples of successful Open Hardware firms. What they have in common is matching their free designs with strong branding. Although there are many Arduino low-cost clones on the market for example, the substantial majority of customers continue to buy from the original provider even at higher costs (Thompson, 2008). The only enforceable IP the original Arduino team reserved was the Arduino brand, which was trademarked and has value to customers because of the reputation and trust the original team garnered from their initial Open Source release and continued support of the community that grew around it (Thompson, 2008). Open Source hardware businesses therefore could protect their brand as one possible strategy. The cost of a trademark is a tiny fraction of the cost of obtaining patent protection, even of a single product in most of the world's markets. In addition to this model, there is also the possibility of a standard reseller business model. For example, MatterHackers sells Lulzbot Taz 3-D printers on their website (MatterHackers, 2016). Numerous other companies sell one another's Open Hardware such as Adafruit and Snootlabs as well as online retail stores such as Amazon, Ebay, and Makershed. It is interesting to note that all of these companies are resellers of authentic Arduino boards.

The nature of collaboration in the Libre Hardware community also enables firms to sell products made with others. For example, Sparkfun is well known for collaborating with small companies and individuals to make new products. The firm Evil Mad Scientist Laboratories used this approach when developing its product Egg-Bot, a compact CNC art robot that can draw on spherical or egg-shaped objects. Entrepreneurs wishing to develop a new Libre Hardware product could work with one of these firms to develop derivative products and split the costs to share the revenue with the more established brands.

Firms can also follow a "package model" where they integrate Open Source components into their existing product lines. For example, a semiconductor characterization equipment firm could sell their own version of Backyard

Brain's micro-manipulator meant for neuroscience experiments (Backyard Brains, 2016) in their own larger characterization suite. As more Open Source components were developed as replacements for components in the suite, the entire system could eventually be commercialized as Libre Hardware. The Open Source labeling already has a strong positive connotation among many technology customers, and some have speculated it could be the next *organic or fair trade* (Gibb, 2014) label. Currently Open Source is becoming increasingly viewed as an ethical bonus as it has value to firms as good will. The Open Source labeling has already resulted in misuse and abuse by some companies that do not develop and release Open Source technologies however. The Open Source Hardware Association is trying to rectify the abuse by providing a certification program.[6]

It is also possible to use open technologies strategically to create a market by driving open standards. For example, Tesla, the electric car company, recently announced it was "open sourcing" all of its electric vehicle patents (Musk, 2014). Although, technically it was not "open sourcing" since there is no license to back up its promise not to sue other companies using Tesla's patented technologies it is an important public statement of good will. In this way Tesla is likely to directly benefit from a common, rapidly-evolving technology platform as seen in other open hardware projects, but it could also enhance Tesla's market as it encourages other companies to start building charging stations and other products that would support Tesla's growth (Solomon, 2014).

Similarly, a firm can open source the hardware they sell in order to expand the market of other parts of their product line. This is referred to as a "secondary supplier model" (Buitenhuis and Pearce, 2012), which is best suited for established and larger companies with more experience and existing patents. An example of this approach is used by the Nitrate Elimination Corporation (NECi), which is primarily a manufacturer of enzymes for green analytical chemistry. NECi recently collaborated by open sourcing a photometer, which radically undercut the cost of other methods to detect nitrates (Wittbrodt, et al. 2015). In addition to commercializing the photometer themselves, they released the designs under an open license to encourage citizen scientists, makers, and others to fabricate the devices which would assist in expanding the potential market for their enzymes.

As any firm can manufacture Libre Hardware, the most efficient manufacturer will in the end have the lowest price. It is unlikely that NECi, a small enzyme company, will have the least expensive nitrate testing photometer on the market after a few years of international cloning. NECi is protected from this competition as cloners will drive sales of enzymes, which is their primary revenue stream, but other companies that are solely reliant on income from Libre Hardware may be concerned about copycat businesses. Thus, the logic that drives the common fear that "Open Hardware only benefits cloners" is turned on its head. Cloners can actually extend the reach of an Open Hardware brand and their projects far beyond the original innovators productive capacity. In NECi's case they directly benefit from increased enzyme sales created by cloners.

Cloners can be a threat, however, and there are two approaches to dealing with this threat as an Open Hardware business. The first is to simply harness the Open Hardware community to out innovate the cloners. Sparkfun, a manufacturer of Open Source-based electronics, provides a good example of this model. Their CEO Nathan Seidle explains, "When a company relies too much on their intellectual property they become intellectually unfit - they suffer from IP Obesity. There have been numerous companies in history that have had long periods of prosperity only to be quickly left behind when technology shifted" (Seidle, 2012). Cloners are likely to copy a successful product whether it is open hardware or proprietary. Rather than invest in litigation, Open Hardware companies simply continue to out innovate the cloners and bring better products to the market. In Sparkfun's case, normally by the time another business clones one of their boards and makes it available on Ebay, Sparfun already has the next version in the pipeline, ensuring that they always have a competitive advantage for customers. The second approach also ignores the impact of cloners by focusing on services (as discussed below). This approach is similar to the "secondary supplier model" as cloners may actually benefit from service sales. Open Source firms obviously are not the only ones to innovate, and proprietary firms can benefit from leveraging profit from IP and investing it into further innovation (e.g. IP can help companies raise capital using standard models, and hire more innovative staff). Proprietary firms are, in general, limited by innovation occurring within the firm however, whereas Open Hardware firms can pull in externally generated innovation (Brunswicker, 2013; Brunswicker and Vanhaverbeke, 2015).

4.2.2 Selling Libre Hardware Services

Libre Hardware designers can also sell their expertise as the inventors of the hardware itself. Using this model, cloners are a net benefit as they ensure that the inventor's hardware is more widely spread and thus expands the potential customer base for consulting and other services. This open business model is well established in the software world, where, for example, Red Hat has grown to be $1.79 billion/year company (RedHat, 2016) by providing services on top of their FOSS product line. The service model for Open Hardware businesses can be further divided into five strategies.

First, firms can sell a subscription for a package of services around an Open Source product such as Red Hat uses for its customers. It is already routine for scientists to buy service contracts on expensive scientific equipment (e.g. a scanning electron microscope), and designers of such equipment could continue this strategy to provide a firm source of income. This model would be particularly useful at large research centers for industry, government, or academia where there would be many pieces of equipment which need to be maintained. This model could also be used to sell a membership to use specific resources, Libre Hardware equipment and support through the membership fees.

Second, a firm can offer support and training which could include installation, operation, being "on call", and acute maintenance for repairs or upgrades. There are also numerous revenue streams available for providing training of researchers using Libre Hardware. For example, a firm might write/publish books or magazines about how to build or use Open Hardware (e.g. Make). These can either bring direct revenue (e.g. sale of a magazine) or indirect revenue such as it is used by Instructables, which extracts revenue from advertising. In addition, a firm can offer conferences, courses, certification, workshops, or training on how to build, use, and upkeep Libre Hardware. Open Source Ecology makes use of this model, for example, in their workshops (e.g. in aquaponics greenhouse workshop where participants pay a fee to take the mini-course) (OSE, 2016).

Third, a firm can be based directly on consulting for clients to make more sophisticated versions of Libre Hardware. Even Type 1 scientific groups that are comfortable building Libre Hardware for themselves may not have the time or expertise available to easily enhance the equipment for a customized experiment or for unique scenarios and special cases. In all three types of Open Hardware, scientific customers may appreciate this service. In addition, the original inventors of widely-adopted Libre Hardware are often the first to know of new improvements, derivative versions, and innovations. This knowledge can be an extremely valuable asset to be monetized in a number of ways. This type of service can also include guest lectures and corporate speeches. Finally, this type of service-based business model would match how university laboratories normally operate. A firm could obtain revenue from grants, donations, sponsorship, or public funding to design Libre Hardware to solve specific problems. This funding could be in the form of conventional research grants, but would also include Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) funding in the U.S. The SBIR program encourages small businesses to engage in Federal Research/Research and Development (R/R&D) that has the potential for commercialization. The STTR is another program that expands funding opportunities in the federal research and innovation arena. Central to the program is the expansion of public/private sector partnerships to include the joint venture opportunities for small businesses and non-profit research institutions. In the STTR program, the small business is required to formally collaborate with a research institution in the early phases. Programs such as these are amenable to Open Hardware businesses.

Fourth, a firm can service a "producer coalition" (a coalition/foundation/or consortium model). Such a partnership could be commissioned by a group of manufacturers to solve a specific problem within the field (Bruns, 2001). In FOSS these coalitions are well known (e.g. the Document Foundation, which is an independent self-governing entity that supports LibreOffice). A recent coalition involving educational institutions and more than ten companies in Canada can illustrate how such a business model works in practice for Open Hardware (Pearce, Babasola and Andrews, 2012). Due to the combination of a new large feed-in-tariff for solar photovoltaic (PV) technology in Ontario, driving an enormous increase in PV deployment and the historic relatively intense snow in Canada, there was a concern in the local industry on the effects of snow cover on PV yield (Buitenhuis and Pearce, 2012). PV developers were particularly interested in the optimization their systems. By 2012 there were few published studies that quantified the effects of snowfall on PV and none of them offered estimations of snow-related solar energy losses. The more complete studies using field data that have been done were carefully guarded as IP by PV developers. In order to overcome this proprietary knowledge blockade for all developers and systems owners in Canada, an Open Hardware-enabled PV snow study was initiated (Pearce, Babasola and Andrews, 2012). Ten PV companies donated their equipment for testing with two critical guidelines. First, the aggregate results would be published in an open literature (although the company's product results would be given to them individually). Second, at the discretion of the corporations, their results would only be referred to in generalized terms in such a way as to make the products non-identifiable in the public realm. These two clauses allowed for an open generalizable model to be created while, at the same time, protecting all of the participating companies from any competitive disadvantage from embarrassing results. In this way, there was a benefit to the firms to participate in the study as none of the companies were either able or willing to single-handedly fund such a comprehensive study individually. By working collectively under a carefully designed set of "memoranda of understanding" (MOUs), however, the study was created and concluded successfully (Andrews et al., 2013).

Finally, a firm can support other Open Hardware firms in their development. For example, Seeed Studio is a hardware innovation business from mainland China which works closely with technology providers of different scales. When an Open Hardware firm has prototypes which are ready to iterate, Seeed helps produce copies from 1 to 1,000 or more using in-house engineering, supply-chain management, agile manufacturing, and distribution in addition to access to investors.

4.3 Business Models to Serve Scientists: Outsourcers (Type 3)

For the third type of scientist, firms can provide an online service based on Libre Hardware, e.g. perform experiments for scientists. This business model is merely an extension of the path that scientists often take to complete complex projects: first, conducting experiments with students and technicians in their lab; then, moving to other labs within their institutions (generally professionally-staffed facilities where researchers can purchase time on equipment or pay for staff to run experiments on expensive equipment) and, finally, to labs elsewhere. To enable this progression, the company, Science Exchange, meets the demand for outsourced access to core facilities and services by providing an online marketplace (Science Exchange, 2016). Analogous to consumer platforms such as Etsy, Science Exchange connects core labs with scientists who need to run experiments (Gould, 2015). Small Open Hardware companies that specialize in a single technique could already offer their services on their website, but also on platforms like Science Exchange to out-compete more conventional core facilities using proprietary equipment. Core facilities have, however, the full time staff often needed to solve complex, multidisciplinary problems as well as to implement and validate lower-cost Open Hardware-based solutions. Having a hub for research institutions to find the right collaborators and pay for experiments in timely manner helps to monetize the existent bartering system, but also provides a solid platform for funding Libre Hardware development. For instance, core facilities which have a geographically-isolated franchise on a specific type of experiment could pool resources to develop a lower-cost libre equivalent of proprietary tools.

5. Discussion

Libre Hardware businesses already benefit from potentially lower costs as discussed above, but there are several other advantages they enjoy. By avoiding IP-based licensing models (e.g. involving patents, lawyers, legal fees, lawsuits, NDAs and other secrecy agreements) Libre Hardware firms have substantially reduced legal fees compared to more conventional businesses. Today, many firms shockingly spend more on legal fees than engineering. For example, both Apple and Google spend more on legal fees than R&D (Covert, 2012). Libre Hardware companies often benefit from a large and vocal user community, which can significantly reduce the costs of product support because questions are handled in on-line forums by other customers (who are often producers themselves). The same Open Hardware customers also reduce marketing costs as they spread freely the benefits of the libre technology around the globe. In addition, Open Hardware is easier for 3rd parties and other companies to create their own revenue streams by offering support for libre products. This makes support faster, better and less expensive for libre products, which further increases overall value of the product. Libre Hardware companies can also benefit from better employees. There is already a relatively well established benefit for software developers who work for FOSS companies as their individual name can be associated with their work (Lerner and Triole, 2000; Marz, 2010). The same benefit for employees would be expected to occur for Libre Hardware companies.

Despite the known benefits, there are still considerable limitations to the overall Open Hardware approach specifically when it is used in a distributed manufacturing context. For the latter, the "prosumer" must be technically sophisticated to fabricate the products from open digital plans. Many laboratories do not have the necessary skills to do this effectively. In particular, labs may not have the equipment to perform validation and calibration, and the Open Source business community is not well matured in this area, resulting in holding back adoption for a wide range of sensitive instruments.[7] In addition, self-fabricated equipment can be held back for not meeting regulatory, industrial, or consumer-quality standards. Further research is needed in this area by Open Hardware firms. Any organization or even a project has capital requirements: even if these requirements are only quantified in terms of intangible capital and time (e.g. the "opportunity cost" of a scientist donating her own time to Open Hardware development). These requirements can vary widely depending on complexity of the project, skill, and experience of the team. For small projects, this can often be absorbed by the normal operating costs of a research group, but for larger and more sophisticated projects to develop a new Open Hardware-based scientific tool can involve a large investment whereas, as pointed out before, funding agencies and for-profit entities are more comfortable funding proprietary development. This limitation impacts negatively the necessary resources for research and development, preventing individual labs from developing more sophisticated Open Hardware products. In addition, this conflict with funders can result in Open Hardware businesses being converted to proprietary hardware. This is what happened in the case of MakerBot, which was previously an Open Hardware 3D printing company. It was the largest and most successful prosumer 3D printing company five years ago, but it has ever since converted to a closed source ecosystem as it grew. It was purchased in 2013 by a conventional additive manufacturing company, Stratasys, for $403 million. The abandonment of the Open Hardware *ethos* jeopardized the support from the community. In addition, supporters and customers were outraged by the sudden change in licensing of their files on the MakerBot online service, Thingiverse, as the company attempted to patent designs which were freely uploaded, deleting previously supported documentation, and only releasing new printers and software as proprietary technology. As researchers have observed, MakerBot initial proprietary designs were a complete failure from an engineering perspective (Benchoff, 2016). Their "Smart Extruder" was so poor that it resulted in a class action suit against Stratasys.[8] Compounding failures have largely destroyed the company as their 3D printer sales have plummeted. More recently MakerBot announced it was laying off its entire manufacturing workforce in the U.S. and outsourcing it all to China (Benchcroff, 2016). Although this example may serve as a cautionary tale for a company against turning its back on the Open Source community, there is real pressure for companies to pivot towards a proprietary model because the open models outlined in this article offer currently few examples of success.

A second limitation of the Open Source model is that simply making a project or product open does not guarantee a large community building upon one another's designs. The majority of Open Source in principle (e.g. all the code properly licensed on Github or the designs on Youmagine) has not yet been modified or improved by others in practice. Having a successful project involves recruiting core developers, promoting and advertising a project (Vickery, 2015). This level of commitment to hardware development is uncommon in scientific research labs as the financial incentive a company has to do it is rarely present. For academics, the creation of academic journals such as the *Journal of Open Hardware* and *HardwareX* may provide the necessary compensation through peer-reviewed articles and citations.

With these limitations in mind, the evidence across a wide range of experimental sciences indicates that a Libre Hardware approach to equipment development may result in lower costs. Lower costs may, however, not even be necessary to out-compete proprietary equipment vendors because of the increased value they provide to scientific communities. To illustrate this non-intuitive result, consider the following situation. An alumnus of the university has become the CEO of a medium-sized power electronics firm and offers the university a collection of free power monitoring tools. In a large power electronics experiment, these tools represent a relatively small cost, but in general, university researchers are on limited budgets which they attempt to use as efficiently as possible. It is thus tempting to accept the zero cost tools. However, the tools are also proprietary and contain proprietary firmware, so the experimenter does not know exactly how they work and can not fix them or modify them. By accepting the zero cost tools, the university is exposing themselves to exorbitant future costs. If the energy system is large and complex, going back and retrofitting the entire system is far more costly than purchasing components, building, and installing libre monitoring hardware initially. If the generous CEO is forced out of business during a takeover of his company the new parent company may discontinue support for a specific tool or the entire tool line, creating an enormous cost for the university researcher. Similar situations can occur if a proprietary vendor loses key staff, cancels support for a product for any reason, or goes out of business. For this reason, even "free" proprietary equipment may not be able to compete economically with Libre Hardware. Scientists are specialists and thus more technical customers when considering scientific hardware. As scientists would be likely to purchase more valuable equipment (because of the value of greater control), particularly if the price is lower (as it can be with a healthy profit margin for Libre Hardware), proprietary vendors can be assumed to lose market share and be forced out of business by Libre Hardware rivals.

For less technically-saavy customers this trend is not as clear. Although the average consumer in many places with a vibrant Open Source community can already realize significant economic benefits from purchasing a RepRap 3D printer to manufacture goods for themselves (Wittbrodt, et al., 2013), the average consumer is far less technically saavy than any laboratory that itself might outsource manufacturing. For this reason the competitive pressure from distributed manufacturing of Libre Hardware would seem to be focused on engineers, applied scientists, makers/tinkerers, hobbyists and first adopters until the ease of use for both digital manufacturing hardware (e.g. laser cutters) as well as software (e.g. CAD programs) becomes sufficiently user friendly that average consumers can operate them easily.

Consider the economic performance of Aleph Objects (manufacturer of the LulzBot 3D printers discussed in 4.2.1) compared to the proprietary MakerBot. Aleph Objects was named the fastest growing privately-held computer hardware company in the United States by Inc. magazine by achieving a 3-year revenue growth of 2,782%, earning the #122 spot in the 2016 Inc. 500 (Aleph, 2016). For the second quarter of 2016, Aleph Objects reported revenue of US$5.8 million, recording four consecutive profitable quarters and an 83% improvement in year-over-year revenue versus the second quarter 2015 (Aleph, 2016). Aleph Objects grew to 146 employees who help operate their cluster of 155 self-replicating machines, running continuously and manufacturing in the U.S. Conversely, MakerBot, a formally much larger company with considerably more resources sold only 1,421 3D printers in the same market between December 31st, 2015 to April 4th, 2016 (MakerBot, 2016). MakerBot laid off 100 of its approximately 500 employees and closed all three of its retail locations in Manhattan, Boston, and Greenwich (3DPrint, 2016). In October of 2015, MakerBot laid off an additional third of its workforce and closed one of its Brooklyn office spaces (Benchoff, 2015). More recently MakerBot announced a further 30% cut in staff (Petch, 2017). Meanwhile, Aleph Objects, which continues to manufacture in the U.S., expanded distribution channels with a new warehouse in Sydney Australia to compliment its warehouses in the UK and Canada (Aleph Objects, 2016b). These facilities serve Aleph Objects' customers in over 85 countries around the world. Data on economic performance of Open Hardware companies in comparison with companies selling proprietary hardware is challening to obtain, but the example of Aleph Objects vs. MakerBot suggests that it can be profitable to stick with an Open Source model.

The body of literature covering the development and commercialization of Open Source technologies is now substantial. Considering only the literature on FOSS, there are important findings which provide insights into Open Source hardware development and community dynamics. Although there are distinct communities, licenses, models, and tools they often overlap with the needs of the Open Hardware community. As FOSS has come to dominate the software industry, it is possible that Open Science Hardware may do the same to manufacturing in a wide range of products. The literature summarized here indicates that scientific instrument makers might be the first type of consumer to create a larger Libre Hardware market share. These technically saavy consumers would be followed by progressive waves of less technically-inclined consumers until the market is saturated by Libre Hardware projects and firms using one of the business models outlined in section 4. This opens up the possibility of Libre Hardware to reach different markets for broader socioeconomic benefit.

6. Conclusions

This article has reviewed the evidence found in the literature that shows the technological sophistication of low-cost digital manufacturing hardware has reached a critical point. It has been shown to catalyze the growth of Libre Hardware, which has, in turn, gained significant traction in the scientific hardware community. Using an Open Source approach results in more control by scientists of their instruments, but also substantially lower costs in comparison to proprietary ones. This evidence was then used by treating scientists as consumers to develop a collection of examples of business models. Profitable Open Hardware-based business models for selling products to such scientists were identified and illustrated with successful examples for three core types of hardware customers. These business models were generalized to other types of customers who are capable of distributed digital fabrication of open designs to meet their needs. The results indicate that Libre Hardware businesses should target technically sophisticated customers first and, as usability matures, businesses can expand markets for Libre Hardware to less-technically saavy customers.

Notes

[1] The RepRap 3-D printer is a machine that is capable of making its own parts. Several RepRap designs have been developed that can fabricate far more than half of their own parts.

[2] A 3D printer builds up a three dimensional object by depositing successive layers of material that are following computer control. Most RepRap 3D printers use an Arduino microcontroller board or compatible Open Sourceboard to operate.

[3] Exceptions to this orientation of procurement departments is to be found at CERN (the European Organization for Nuclear Research), which is more recently seeking alternatives to IP-driven technology transfer.

[4] For example, the Open-Sensing Lab was funded by the U.S government to develop new approaches to precision farming under a changing climate. Specifically, the Open-Sensing Lab is investigation sensor-systems of low enough cost and high enough accuracy to be used across most agricultural settings and for research in environmental science (OSL, 2016).

[5] As it is performed regularly in the industry through plugtests or plugfests to ensure interoperability in observance of an industry standard.

[6] http://certificate.oshwa.org/.

[7] It should also be pointed out, however, that even when attention has been paid to these issues, as with the Safecast project (http://safecast.jp/en/), it has not yet substantially changed the market for radiation detectors.

[8] https://cdn-shop.adafruit.com/pdfs/makerbot/classaction.pdf.

Competing Interests

The author has no competing interests to declare.

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How to cite this article: Pearce, JM 2017 Emerging Business Models for Open Source Hardware. *Journal of Open Hardware*, 1(1): 2, pp. 1–14, DOI: https://doi.org/10.5334/joh.4

Published: 21 March 2017

]u[*Journal of Open Hardware* is a peer-reviewed open access journal published by Ubiquity Press.

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