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Business Models for Open Source Hardware Repositories

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Abstract

Free and open source hardware repositories provide massive public good, but funding their operation has proven tenuous with conventional business models. This study evaluates business models to foster that public good. Business models for online design repositories are reviewed and a new model is conceptualized to fund repository operations. The greatest added value an open hardware repository brings to the user-developer community is validation and vetting of the designs. A business model was proposed that uses revenue from the vetting process to fund validation studies and sustainable operations of the open hardware repository itself. As the return on investment of laterally-scaled open hardware that can leverage distributed manufacturing has the potential for creating enormous value, maintaining repositories for this hardware enables vast wealth generation for everyone. This is the first study specifically focused on ways to ensure economic sustainability of open hardware repositories.

Introduction

Free and open source software (FOSS) is software that is both free software (users have the freedom to use, copy, study, and change the software in any way, as well as to sell it) and open-source (the source code is accessible). With the majority of large companies now contributing to open source software projects, it has become the dominant form of technical development in software engineering (LeClair, 2016). Free and open source hardware (FOSH) uses the same sharing philosophy as FOSS (Powell, 2012). FOSH is hardware whose design is shared so that anyone can study, modify, distribute, make, and sell the design or hardware based on the design. FOSH provides the "source code" for physical hardware including the bill of materials (BOMs), schematics, computer aided designs (CAD), and other information such as detailed instructions needed to recreate a physical object (Gibb, 2014). As well established in FOSS development, FOSH has now demonstrated improved

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product innovation (Dosemagen, et al. 2017), which can be driven by company-community collaboration (Ezoji, et al., 2020). FOSH is growing rapidly, but is roughly 15 years behind FOSS in maturity (Pearce, 2018). At a societal level, as open source development for both FOSS and FOSH has been shown to increase innovation (Weber, 2004; Maxwell, 2006; Penin, 2011; Dosemagen, et al. 2017) and decrease costs (Riehle, 2007; Pearce, 2015; Dryden et al., 2017). For example, a recent review of hundreds of published scientific open hardware found that FOSH provides economic savings of 87% compared to equivalent or lesser proprietary tools that increased to 94% for those that used open source electronics and open source 3-D printing (Pearce, 2020). The rapid technical evolution of FOSH is already clear for both the electronics industry where many commercial firms sell FOSH (Ngo, 2019; Hannig & Teich, 2021), and the additive manufacturing industry where millions of free 3-D printable designs already exist (Wittbrodt et al., 2013).

The shear volume of FOSH designs has become an issue. With millions of designs circulating in hundreds of databases and websites, finding high-quality vetted designs is challenging and clarifies the critical need for centralized trusted databases of vetted FOSH. When vetted designs are made possible for distributed manufacturing from local resources real value can be generated (Pearce, 2015). The efficacy of this approach on a limited scale was witnessed as a solution to the COVID-19 personal protective equipment (PPE) shortage in the U.S. that was solved in part by an agreement between the NIH, the FDA and VA. The NIH leveraged their existing 3-D Print Exchange, a database of FOSH that can be produced with additive manufacturing, to accelerate the distributed manufacturing of 3-D printed protective gear for COVID-19 response. Users share and find designs that are either community- or clinically-relevant after having been vetted by the FDA or VA. This approach supported by the maker community was readily-compatible with distributed digital manufacturing. Open Source Medical Supplies has documented how more than 48 million FOSH medical supplies were produced by the community during the 2020 COVID-19 supply chain crisis. Similarly, for any central repository for a specific kind of FOSH to be most effective, it needs to be housed in a trusted central authority and that authority comes from vetting using openly accessible standards. The costs to vet or validate a FOSH design can vary widely. For example, some FOSH repositories that focus primarily on toys and games (e.g. 3-D printing mini-figures for board games) can rely on relatively low revenue business models and basically only cover website maintenance and hosting costs (that do increase with download volume). The standard method to vet a FOSH, however, would be to recreate the design physically from the supplied documentation and then test the device to ensure that it met the specifications of the design. So, for example, to vet an open source multichannel pipette a tester would fabricate the device and then test it for ISO 8655 compliance (Chinchane, et al., 2022). This would have a modest cost associated with the vetting. Repository owners focused on other FOSH such as those in the regulated spaces need higher revenues (e.g. to fund FDA approval for class 3 medical devices can cost millions of dollars per device). So how can a FOSH database, especially for those focusing on high-value regulated products remain economically sustainable? This article reviews existing business models used by FOSH databases and presents a novel business model that focuses specifically on enabling funding of such potentially high-cost and high-value validation work.

Approach

As a company's long-term competitive success depends on its ability to create an innovative business model (Gassmann, et al, 2014), this analysis draws upon previous research on business model innovation, which focuses on the concept of business model configurations (Taran et al., 2016; Remane, et al., 2017). All of the business model patterns in this area fall under the digitization pattern, where a conventional physical product is offered as a digital good (Gassmann, et al, 2014), but here the method of extracting revenue for validation will be examined. In addition, the specific twist on all of the following business models is that they are supported by the core open source alliance business model, where the core content is developed by the

community (Tapscott, Lowy & Ticoll, 2000). First the current business models used to maintain FOSH databases will be reviewed and an example of each discussed and mapped to existing business model configurations. Then a new model that is able to sustainably fund the vetting process and a FOSH repository will be proposed and analyzed.

Model 1: Charity

There have been business models used on the internet (Doligalski, 2018) that provide free content via a charity like Wikimedia (Rappa, 2001). The *Journal of Business Models* itself functions in part this way providing free information on business models (Nielsen, Haslam & Turcan, 2013). A good example model in this space is the Appropedia Foundation, which is a 501c3 charity that runs Appropedia, which is the largest wiki-based website that contains FOSH solutions to poverty, environmental degradation and international development. The website is organized into portals that are groups of articles arranged by topics that focus around appropriate technology for sustainable development. Topics include construction, energy, food and agriculture, health, and water. The open source appropriate technologies (OSAT) housed on Appropedia directly address the UN's sustainable development goals (SDGs) and are both contributed to and used all over the world. To maintain the website the Appopedia Foundation solicits donations and competes for grants. It generally does not seek funds for vetting technologies, but enables a volunteer mechanism where users (e.g. university labs) can alter the status of a FOSH design indicating that it has been replicated.

Model 2: Goodwill for parent company

Autodesk, Inc. is a multi-billion dollar per year multinational corporation that develops software for a wide range of industries. To buy business goodwill in the burgeoning maker community, Autodesk bought and maintains Instructables, a website and platform where users can share their ideas and collaborate with a variety of do-it-yourself (DIY) and FOSH projects. Instructables has a three-part strategy: 1) make it easy to learn how to make anything, one step at a time, 2) allows users to share as everyone has skills to share; 3) making things makes people happy. Instructables also has a formal "be nice" policy where they ask that commenters be positive and constructive. Overall, this approach has worked; Instructables is a vibrant community of curious makers, innovators, teachers, and life-long learners who love to share what they make. This relationship building is what makes it successful and is observed in other successful business models (Hollensen, Eskerod, & Ulrich, 2020). They also have prizes and contests to encourage people to provide content and use cartoon robots to make the site seem fun and approachable. Autodesk earned business goodwill in the maker community and encourages the use of its products. This business model is primarily a brand integrated content business model (Rappa, 2001), where the manufacturer of other products creates content for the sole basis of product placement. Another way of looking at this business model is an extreme version of the add on model, where a business offers a basic product at a competitive price and charges for several extras (Gassmann et al., 2014). In this case the basic product is offered free and the extras are entirely different products purchased in part because of increased goodwill. This model, however, does not provide funding for validation of any type other than users posting remakes and allowing for comments.

Model 3: Advertising

Advertising based business models are well known and described in the literature (Hanson, 2000; Rappa, 2001) and in this case it is following a free content model (Osterwalder & Pigneur, 2010). Running advertising on the OS database website is a potential source of revenue as DXFProjects does on their website that houses FOSH designs that can be manufactured with a CNC mill or a CNC laser cutter. They also are supported by a link to premium designs sold on Etsy. This funding model only covers the website operation and advertising revenue does not fund testing of any kind.

Model 4: Premium memberships

Membership based business models have proven successful (Tuff & Wunker, 2010). This approach to generating revenue to maintain an open source database would be to offer premium memberships that

would provide users access to Google Analytics data and other potentially valuable information. An example of this approach is Academia, which provides a database of open access preprints of academic articles. Academics can pay to have access to this analytical information, but also to spread their work more widely to improve their academic reputation. This reputation-based value creation may be of interest to some FOSH developers as employers in the open source development space often look to databases as portfolios of potential employees.

Model 5: Host some paid-for content

Following on the advertising approach a FOSH repository can also generate revenue to host paid-for content designs. This business model is normally considered to be an online broker like Air BNB (Strauss & Frost, 2014). A good example in this space would be MyMiniFactory, which is a 3-D printing design repository that contains both FOSH designs and designs that must be purchased. The profits from the latter can fund those of the former. In addition, because the cost to fabricate most of the designs is so low, MyMiniFactory does provide a basic vetting of "is it printable" by only allow proven printed designs on their site. Most designs are tested for 3-D printing by users, but they also do some printing.

Model 6: Service for customers

Business models associated with providing services on top of open source software projects are well known (Shahrivar, et al., 2018) and are even starting to form for open hardware (e.g. distributed I/O as a service (Pontarolli, et al., 2022)). Service, however, can also be done for customers purchasing related products that add value. As an example, Prusa Research is a large open source 3-D printer manufacturer, which utilizes several established open hardware business models (Pearce, 2017) to be one of the most successful manufacturers in the desktop space. Prusa Research maintains Printables, a repository of FOSH that can be manufactured on their 3-D printers. This can be viewed as a shared infrastructure among competitors business model (Weill & Vitale, 2001), but Printables provides easily accessible service for their customers that directly couples to their products. Printables has a long list of features (largely based on user feedback), that include community contests, user groups, events, rewards, and a selection of social media tools. Anyone can use the database and the FOSH even if they do not use a Prusa printer. Each design uploaded to Printables, however, de facto increases the value of the Prusa's main product as it can be used to create value for their customers. Similar to MyMiniFactory, which is in the same technical space, there is no funding for validation testing.

A new FOSH business model is needed

The costs to validate a design can vary widely depending on the technology, from simple tests that could be completed in hundreds of university laboratories for little or no cost (e.g. mechanical properties testing), to those that are quite substantial (e.g. clinical trials of medical implants). Validation could come from external partner organizations whenever possible to minimize the vetting costs, but another approach would be for the open hardware database owner to charge for validation of open source designs. To fund these tests a new business model focused specifically on leveraging validation payments to provide for sustainable operation of a FOSH repository is presented here.

Key Insights

The value of having a design validated can be substantially more than even the highest validation costs, particularly if it is open source and the values are summed globally. How this new business model takes advantage of this value landscape is illustrated in Figure 1.

In Figure 1, the green arrows represent a transfer of wealth and the black arrows represent a transfer of FOSH designs. Red open hardware symbols are untested designs and green-rimmed open hardware symbols have been vetted using an openly accessible standard. As can be seen in Figure 1, first a funder invests in a developer to make open hardware. This could be an open hardware company paying an employee, a philanthropist funding an NPO, a group of Kickstarter backers, or user-developers making a design they want. The developer uploads the design to the FOSH database. The FOSH design has value, but it may be relatively low because it has not yet

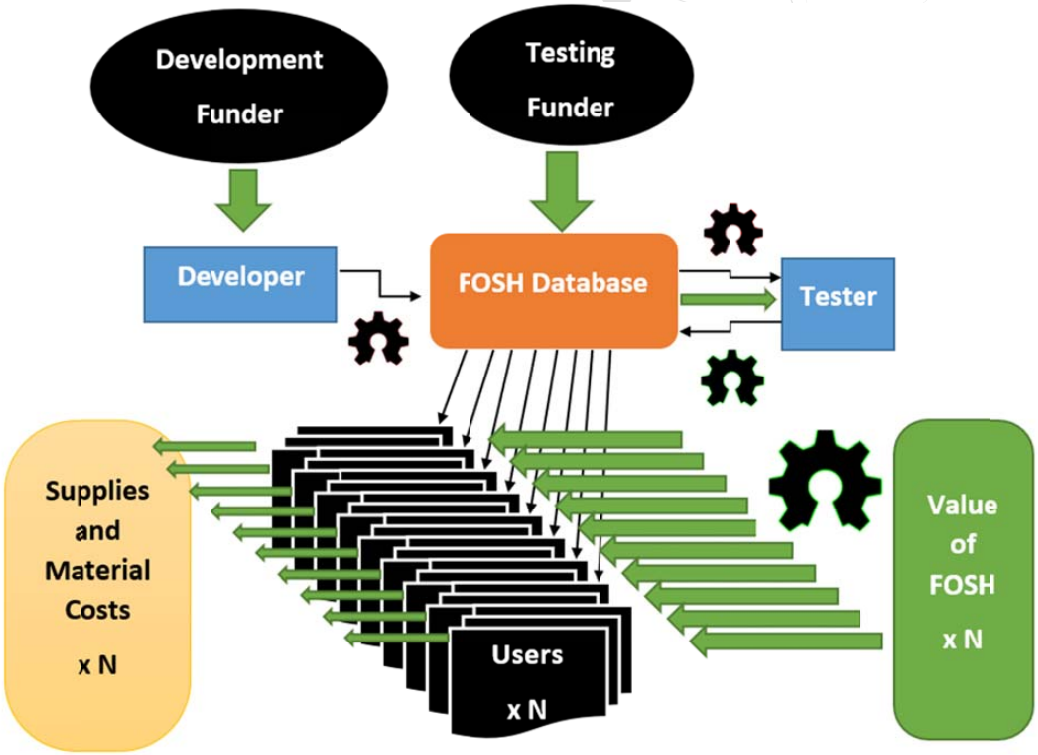

Figure 1. Proposed FOSH database business model.

been vetted (red rimmed open hardware logo). Another funder (or the same one that financed the development) anticipates additional value if the design is vetted and pays the owner of the FOSH database to have it tested. The FOSH database operator pays the tester to test it and additionally uses some of the funds to maintain the database. After testing, the potential value of the open hardware increases substantially (green rimmed open hardware logo). Users can download the FOSH design for free. Each user, however, must make a small investment (e.g. for materials, supplies and their own time), which is shown as small green arrows, and each user can expect to get about nine times their investment out by fabricating the FOSH (noted by the large green arrow of value going to the users) (Peteresen, 2017). This micro investment and ROI can be multiplied by the number of users, N, (Pearce, 2015), which can number in the millions. The ROI for an individual user is good, but the aggregate ROI for the investment of both initial funders (development and testing) can be astronomical in terms of public good and wealth generation (Pearce, 2016). For example, with millions desktop 3-D printers being purchased annually, and the proliferation of open source digital designs for 3-D printed products, a study was conducted that analyzed the wealth generated by the top 100 most popular FOSH designs posted on the YouMagine repository (Pearce & Qian, 2022). If distributed recycling and additive manufacturing is used the means of percentage savings using commercial filament, commercial pellets, recycled commercial pellets, and self-recycled consumer plastics are 82%, 94%, 97% and 98%, respectively. If scaled to the entire U.S. from household plastic waste, the potential for wealth generation is over $359 billion/year for offset filament purchases or over $7 trillion/year for products (Pearce & Qian, 2022). Such scalability is important for business models in general (Lund & Nielsen, 2018) and although all of the wealth does not accrue to the primary business, value is added. The highest value products are the ones that would involve the most testing (e.g. medical equipment). The potential for wealth generation is clearly substantial, however, who will pay for the testing to extract the full vale from FOSH designs?

There are several entities that would pay for such a service:

- Firms using any of established open source business models (Pearce, 2017; Gambardella, & von Hippel, 2019). These companies would want their technologies listed to sell more products by being able to claim validation for function. Many FOSH businesses already expend capital to take the time to have their products certified by the Open Source Hardware Association, which determines appropriate open source license and full FOSH documentation of the design.
- Similarly, companies with some social mission may develop technologies that are appropriate for the COSD and want them included (e.g. Google X – now the X Company).
- Nonprofit organizations wanting their technical developments to gain scale to support their mission directly and for notoriety that can benefit them by increasing donations. For example, Public Labs may want to have their PaperCraft Spectrometer validated so that it can be used in citizen science campaigns to map local pollution for a lawsuit against a polluter. This class of potential clients would also include universities that may view FOSH validation tests to being synonymous with article processing fees for academic articles and may similarly be willing to invest to scale their project and prestige within their specific technical community (Gibb, 2014).
- Nations or groups of nations (e.g. the UN) interested in solving problems for their citizens. For example, India published a list of products it needed during the pandemic and if they could be had with distributed manufacturing may have paid for the most critical designs to be validated. This is particularly important as FOSH not only can directly fulfil needs but it also can be used for capacity building for low-middle income countries (LMICs) (Bezuidenhout, et al., 2022).
- Communities of FOSH/FOSS developers ready to take their innovations global (e.g. if a particular technology appears to be gaining traction yet it is not clear it is safe, reliable, etc.). For example, Open Source Ecology members may want to have their open source Seed Eco-Home tested and validated to expand the market to different areas with different building codes to be able to sell access to their training sessions and builds.
- Local communities or those with common interests perhaps through aggregating services and crowdfunding (Gassmann et al., 2014) like KickStarter, GoFundMe, Patreon, Wefunder, Indiegogo, or Chuffed that want to see specific technologies scale for the betterment of the world and themselves.
- Philanthropists and philanthropic organizations that are interested in maximizing the social return on their philanthropic investments. For example, effective altruists follow a philosophy and have now developed a community focused on maximizing the good they can do through their careers, projects, and donations. Effective altruism is complimented by open source thinking (Bhandari, 2022). The ROIs for open hardware are formidable and if there are FOSH that target particular social causes they would appear to be a good match for funding both the development and testing. This is particularly true for scientific hardware, and offers the potential to transition all of science towards more plural and democratic sociotechnical systems (Arancio, 2019; Arancio et al., 2022) as well as appropriate technology for developing countries and resource constrained communities (Omer et al., 2022).

Thus, one of the primary functions of the FOSH database-related business model would be determining appropriate validation tests for FOSH, developing open standards for those tests, and then either performing or arranging for the outsourcing of such tests. There are entities that are following non-open source analogues of this business model already. For example, the Electrical Safety Authority is a self-funded non-profit association that offers electrical product safety, contractor licensing and electrical inspection for fees. Their revenue comes from their inspections both of hardware inhouse and onsite testing. FOSH database owners would use the

leverage of the higher value of validated FOSH to target customers in the seven preceding categories to pay for validation and repository maintenance.

Discussion and Conclusions

The largest expense for running a high-value FOSH repository is the cost of validating FOSH, which can involve capital-intensive scientific equipment and costly expertise. To overcome this challenge, while at the same time building a self-sustaining organization to maintain the repository, a partnership model is recommended where 1) FOSH companies, 2) social-mission companies, 3) nonprofit organizations building FOSH, 4) countries or groups of nations, 5) communities of FOSH developers, 6) local communities, or 7) philanthropists or philanthropic organizations. These seven potential customer classes would provide either in-kind testing, or fund the testing of specific FOSH to advance their own interests. Thus, one of the primary functions of the FOSH repository-related business model would be determining appropriate validation tests for FOSH, developing open standards for those tests, and then either performing or arranging for the outsourcing of such tests for a fee a part of which would sustainably fund the repository. As the return on investment of laterally-scaled FOSH that can leverage distributed recycling and manufacturing has the potential for creating enormous value, maintaining repositories for this hardware enables vast wealth generation for everyone and could have a profound global social benefit.

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