Journal of open hardware

Jubilee: A Case Study of Distributed Manufacturing in an Open Source Hardware Project

ISSUES IN OPEN HARDWARE

]u[ubiquity press

KELLIE DUNN
CYNTHIA FENG
NADYA PEEK

*Author affiliations can be found in the back matter of this article

ABSTRACT

Manufacturing machines is a challenging task. High-volume sales can offset costs of production, but niche products struggle with viability. Distributed production—having people build their own niche products—is a possible alternative. We examine the Jubilee project, an Open Source Hardware machine with tool changing capability and multiple end effectors designed for distributed production using off-the-shelf and digitally fabricated parts. Since Jubilee's 2019 release, we track its adoption, its online community, and people who have successfully built it. Through analysis of the Jubilee project including 170+ Jubilees built in the wild, interviews with 12 Jubilee builders, and its Github, Discord server, and Wiki, we investigate what aspects helped people produce complex hardware on their own and how they strengthened the design of the product in turn. We find that while self-production is challenging, it can be a viable alternative to traditional hardware manufacturing. Finally, we discuss recommendations for self-produced Open Source Hardware projects.

CORRESPONDING AUTHOR:

Kellie Dunn

University of Copenhagen, DK; University of Washington, US

kelliead@gmail.com

KEYWORDS:

Open Source Hardware; distributed production; machine building; online maker communities; self produced hardware; hardware customization

TO CITE THIS ARTICLE:

Dunn K, Feng C, Peek N. 2023. Jubilee: A Case Study of Distributed Manufacturing in an Open Source Hardware Project. *Journal of Open Hardware*, 7(1): 4, pp. 1–15. DOI: https://doi.org/10.5334/joh.51

1 INTRODUCTION

Unlike Open Source Software, there is a cost associated with reproducing an Open Source Hardware project: the cost to manufacture. Scaling from a single prototype to the manufacture of multiples is challenging and requires specific expertise [16]. To address this, many large-scale Open Hardware projects are supported by companies (e.g. Arduino, Beagleboard, Prusa, or Ultimaker [3, 4, 24, 33]) who take on not only the design and documentation, but also production and sales. Studying Open Source Hardware in the wild, e.g. through sales data and DIY documentation, can help us understand how hardware design engages end users [17, 32, 8, 25].

Powell [23] maps some of the key differences between Open Source Hardware and Software, noting that while Open Source Software has transformed software development and associated labor, Open Source Hardware cannot easily be transformed in the same way, as hardware *manufacturing* depends on very different forms of labor and is done somewhere else—for electronics, oftentimes in and around Shenzhen. Powell argues that while hardware hacking introduces 'new forms of technological citizenship, based on better knowledge about how things work and increased abilities to take apart, repair and reconstruct', Open Source Hardware licenses alone have not profoundly changed how and where hardware is manufactured [23].

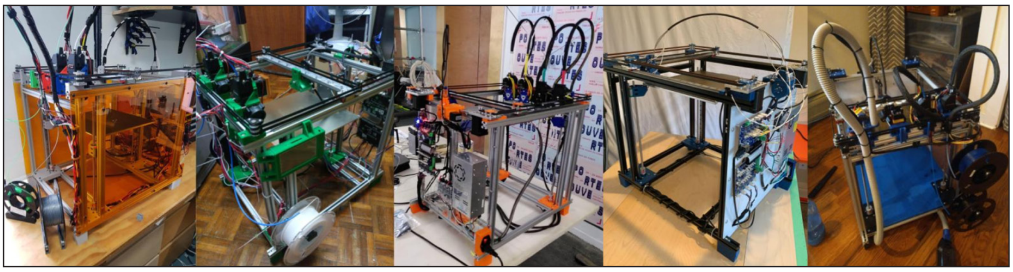

Figure 1 Five Open Source Hardware Jubilee machines, each of which was self-produced and customized by an independent builder.

Prior research has investigated the personal and altruistic motivations of people engaged in software-based peer production [18, 2], how Open Source Software communities are joined [13], and how such communities are sustained over time [12, 30]. These findings are echoed in a study of Open Source Hardware entrepreneurs by Li et al. [19], which finds that their motivation similarly stems from personal satisfaction, reciprocity, and altruism, but also from profit that can be derived through their companies that sell products which are largely conventionally produced at scale. More explicitly, [20] find that Open Hardware companies such as Seeed Studio and DFRobot promote Chinese manufacturing as the production arm of Open Source and maker-oriented hardware designs, e.g., promoting the manufacturing epicenter Shenzhen as 'The Silicon Valley for Hardware'. In contrast to prior approaches of companies working in Open Hardware such as Makerbot, which leveraged its community for free contributions that it could convert into economic value, Lindtner et al. [20] show that Seeed Studio and DFRobot's business model incentivizes community members to constantly create open designs which the companies then produce (in Shenzhen) and sell (shipping worldwide), offering creators profit sharing for sales. However, the Open Source Hardware companies that Li and Lindtner et al. study do not transform ways of physically *producing* hardware, rather still relying on centralized production.

In 'Long Tail Hardware: Turning Device Concepts Into Viable Low Volume Products', Hodges and Chen [14] provide additional detail on the trade-offs between complexity, refinement, and price in hardware manufacturing. They note that while crowdfunding and project incubation can support nascent stages of a product, the typical success story has the potential for high growth and therefore high-volume sales. This is not compatible with niche products. They identify essential elements of what they call the *'challenge of replication'* in hardware production, including finding reliable suppliers and sourcing for components and maintaining manufacturing quality control. While they believe demand exists for niche hardware products, they observe that the realities of production constrain the economic viability of such products, truncating what would otherwise be a long tail of options. They call for future research in new manufacturing solutions for small batches as one way to make niche hardware possible.

RepRap is a notable exception to the rule that Open Source Hardware is centrally produced. RepRap is a community founded in 2005 focused on creating 3D printers that can themselves be 3D printed, which they call self-replication [5]. Many 3D printing companies, Open Source or otherwise, were initially formed through personal connections made in the RepRap community. RepRap positions itself against centralized production and distribution, and rather advocates for the design constraint that the machine itself should be able to produce the majority of its own parts or that they should be readily obtainable off-the-shelf [28]. Project advocates argue that in this way, participants can *"breed the means of production"* rather than buying it. However, *self-produced* RepRap 3D printers are vastly outnumbered by commercially available, centrally-produced Open Source Hardware 3D printers. Having machines available off-the-shelf increases their reach, but limits the customization and adaptability of the machines. Customizability is made possible to some extent by making machines available as kits with various customer options. However, kit options are more limiting than self-production.

Besides 3D printed machines, RepRap also collaboratively develops 3D printer support infrastructure such as firmware and control boards. For example, the RepRap control firmware Marlin [34], first released in 2011, has become the de facto standard for low-cost 3D printers, including Prusa, Lulzbot, Ultimaker, and the CR or Ender series. Furthermore, RepRap firmware is used extensively in machines built for research [29, 11, 15, 1]. This demonstrates how projects with different goals are now supported by shared Open Source infrastructure, combining high-level pieces of centrally produced hardware (such as controller boards) with custom parts that can be self-produced.

Given the state of Open Source machines, we wish to understand if alternative and distributed production and manufacturing methods such as self-production are becoming viable for complex hardware (such as machines) at a larger scale. Furthermore, we wish to understand the possibilities self-production introduces for end-user customization and tailoring of hardware designs. Customization/adaptation of machines is already taking place at a limited scale, for example in one-off research systems [31, 22, 26, 36]. What are the barriers and opportunities currently in place for growing beyond one-offs?

To investigate these questions, we identify the early-stage Open Source Hardware Jubilee Project as an appropriate case study. The Jubilee Project is a motion platform with automated tool-changing functionality which can be used for applications including multi-material 3D printing and liquid handling [35]. The project's Open Source plans were initially released in 2019. Jubilee's hardware was explicitly designed to be assembled from self-sourced and self-produced components, customized, and built by independent makers. However, there is a lack of data on whether or not the project was successful in those design goals. Our initial observations show that despite the complexity of the Jubilee project, many makers have successfully produced and customized Jubilee machines, demonstrating the viability of this alternative production model.

2 METHODS

Our research is based on data collected from three main sources: (1) Jubilee's design and documentation on Github and its Wiki, (2) Jubilee Discord server data, and (3) semi-structured interviews with 12 early builders of Jubilee machines. In this section, we describe our methods for assembling and analyzing these datasets. To contextualize our data collection, we also provide details on the author team.

2.1 RESEARCH QUESTIONS AND DEFINITION OF TERMS

What makes self-production viable for an Open Source hardware project? How might an Open Source hardware project overcome challenges of distributed manufacturing?

For the purposes of this study, we define *decentralized production* or *distributed manufacturing* as the concept of building hardware at or near the location of its use, rather than in a factory; and *self-producing* as the act of gathering, creating, and assembling one's own components for a given project. We also define *end effector* as the different machine heads or attachable tools that can be used for different workflows such as 3D printing and pen plotting. Lastly, we wish to emphasize the difference between a *project* (a set of hardware plans for which the builder must source their own parts) and a *kit* (a set of hardware plans that comes pre-packaged with all of the necessary parts in one purchase from one vendor).

2.2 CASE STUDY DESIGN

Because of its recent launch, its self-producible design, its public development, and its active community, we believe the Jubilee Project to be an interesting case study to provide insight about current challenges and opportunities of self-production and customization in hardware. We approached this study as a single-case design with embedded units of analysis (individual interviews with early builders, community-wide Discord server data, and design documentation).

2.2.1 Why the Jubilee Project?

Jubilee is an Open Source hardware machine with automated tool-changing functionality which can be used for non-load bearing applications including multi-material 3D printing and liquid handling [35]. Jubilee's hardware was explicitly designed to be customized and self-produced by independent makers, and was initially released in 2019.

Jubilee's designers identify 'fabricatability' as one of its principal design goals [35]. They define fabricatability as being made with parts that are available in low volume, or parts that are made with readily available tools and equipment, and with documentation that includes all the details required for making one. A second principal design goal is extensibility, in particular making it possible for end users to customize their Jubilees by installing different end effectors. This demonstrates that Jubilee aims to use alternative and distributed forms of production and to scaffold machine builders with custom applications. Therefore, we believe studying the Jubilee project will give us valuable insights into themes of alternative production and end user tailoring of Open Source hardware designs.

2.2.2 Scope of case

We began studying the Jubilee project and community in March of 2020, and concluded our case study data collection on February 10, 2022, when Jubilee was released as a kit, signifying the end of the project's exclusively self-produced phase.

2.2.3 Data Collected

We collected data from the following sources: Discord, interviews, and design files and documentation on the project's Wiki and Github. Our data collection was vetted by our institute's Institutional Review Board.

To collect data on the project's use of Discord, an online Voice Over Internet Protocol (VoIP) and instant messaging social platform, we introduced a Discord 'Statbot' to the official *Jubilee Builders and Extenders* Discord server, to collect server metrics such as number of members, volume of messages, and duration of voice interactions. This bot was introduced six months after the launch of the public server and collected data over the following 23 months. In this time, the community count more than tripled from 570 members (March 7, 2020) to 1870 members (February 10, 2022). Additionally, we manually tracked how many people on the Discord server were actively building Jubilees by counting the number of images of unique machines, announcements that members had ordered parts, or questions-and-answers involving steps in the build process, and organized this tally in a spreadsheet.

We conducted 12 semi-structured interviews with early Jubilee builders in July of 2020. We recruited participants by posting a Google form signup sheet on the Discord server in the #announcements channel, identifying ourselves as researchers and asking for voice chat feedback on builders' experiences reproducing the machine. Inclusion criteria specified builders who were either in-progress or had already built a functioning Jubilee. Each member was cross-checked against our prior build count to confirm that the interviewee had indeed met our criteria. All interviews were conducted strictly online, with participants located in North America and Europe. To differentiate between the general Jubilee builders active on Discord and the Jubilee builders we interviewed, we will refer to the latter as *participants*. Each interview included questions about the participant's technical background, their experience reproducing the project, their motives to do so, modifications they made, and any difficulties they encountered along the way. Interviews were conducted in voice chat format with the option to share video or images. Interviews ranged from 45 to 120 minutes. Interview recordings were transcribed automatically using the software package Temi, and then inspected and corrected manually by one of three researchers.

We also examined Jubilee's design files and documentation, which included: a bill of materials/shopping list; CAD files available in multiple formats for its printed, laser cut, and machined parts; illustrated assembly instructions in PDF format, which are organized into a series of sub-assemblies; wiring diagrams; G-code config files; slicer setting files; and reference sheets for the many fasteners and parts that need inserts installed. These files are all hosted on the project's Github. The project's Wiki (at Jubilee3D.com) organizes these files in a more user-friendly format, and also includes information about operating conventions, machine usage, a customization library, and general information about the project.

2.2.4 Data Analysis

To capture and analyze interview data, we used a first cycle open coding (or eclectic coding [27]) method, and a second cycle pattern analysis coding method, followed by thematic analysis [6, 7]. Based on our research questions, we developed an a priori codebook of attribute, descriptive, and process codes (for example, *sourcing*, *getting help*, *giving help*, and *customization*). We extended our codebook during the coding process to include inductive codes capturing values (such as *personal motives*, *community motivation*, and *community norms*) for a total of 30 unique codes. Coding was conducted by three researchers, with a minimum of two researchers coding each transcript, using Taguette qualitative coding software. After the initial coding phase, all three researchers individually conducted pattern analysis on our coded data, and met to argue and consolidate our individual analyses into coherent themes. Using these themes, we combined the interview data with our other datasets, e.g., cross-referencing details interviewees mentioned with time-stamped events in our Discord data.

After this analysis, all researchers met again to go over categorical thematic analysis and discussed more in-depth findings from the most salient themes. Of the themes we identified, we include here the subset that we considered most prevalent to this dataset and most relevant to the research questions.

2.3 LIMITATIONS

The majority of our data collection phase coincided with the ongoing global COVID-19 pandemic. This has firstly limited our data collection to methods that can be conducted at a distance—we have never met most of our interviewees nor their Jubilees in person. We acknowledge that studying Jubilee builders and their machines in person could provide us with richer data, however, we believe that the data we collected is representative of the project which itself exists predominately online and whose community is geographically spread out.

Furthermore, there are limitations to our data collection methods. First, we recruited self-selecting interview participants through the Jubilee Discord server. While this recruitment method introduces a selection bias, as these participants may be enthusiastic community members excited to share their work, we believe this data is nevertheless beneficial and may provide richer insight as these particular participants have spent more time on the Discord server. Second, our machine count estimate is limited to data collected from the Discord server where posting is voluntary. Consequently, our machine count is likely missing additional builds from Jubilee builders who either do not self-identify as builders on the Discord server or simply do not participate in the Discord server altogether.

2.4 POSITIONALITY

To provide perspective on how the authors' backgrounds shaped this study, we provide a few details on our involvement with the Jubilee Project. We participate in the Jubilee community, and built two Jubilees ourselves during this study. We regularly participate in the Discord server in text and voice chat and have contributed suggestions and updates to the original design files and the Wiki. We liken this practice of embedded or active community involvement as critical to gathering and understanding our dataset, and comparable to practices in related research. For example, Dasgupta and Hill [10] were active in the online community that they studied, as were Morreale et al. in the Open Source hardware Bela project [21], Buechley and Hill in the Open Source hardware project Lilypad [8], and Qi et al. in the Open Source hardware company Chibitronics [25].

3 CASE STUDY: THE JUBILEE PROJECT

In this case study, we provide a detailed description of the Jubilee project community, based on interview data and analysis of the project's design files, documentation, Discord server, and community Wiki. Based on these data, we estimate that at least 170 people had independently built Jubilee machines by February 2022. Some of these machines are shown in Figure 1. We contribute an analysis of these data, where we identify themes related to distributed manufacturing and self-produced Open Source Hardware. We found that community support was critical for individual success in self-production and customization, and that the project's self-sourcing and self-production model created opportunities for collaborative community-developed design improvements that resulted in a more successful and stable version of this complex hardware.

3.1 PROJECT SUMMARY

The Jubilee machine is an Open Source electro-mechanical device. It is used as a computer-controlled motion platform capable of running G-code. Jubilee is designed with integrated toolchanging: the design separates the motion control from the end effectors, such that the user can design any end effector for the system without needing to modify the base machine in any physical way, and automatically switch between different end effectors. Most of the Jubilees represented in the community's Discord server and among our participants used 3D printing extruder end effectors for multi-material printing. However, we also found examples of other customized end effectors in use for tasks such as pen plotting, and end effectors for scientific lab applications such as microscope cameras, sonicators, and syringes for automated liquid handling.

We began our case study of the Jubilee Project in March of 2020. In May, one of the community members created the project's collaborative Wiki at Jubilee3d.com. We conducted interviews with 12 Jubilee builders in July 2020 (see Section 2.2.3 for interview details), and we continued ongoing tracking and observation of the Discord community, Wiki, and Github through February 2022. On February 10, 2022, version 2.2.2 was released as a complete kit for sale by a vendor in the United States, signifying the achievement of a stable and marketable design. This marked the end of Jubilee existing exclusively as a self-sourced project, and thus a natural end of our case study period. A more complete timeline of the Jubilee project is represented in Table 1.

For the duration of this case, Jubilee was an entirely self-sourced and self-built project. A Jubilee frame (the machine not including any end effectors) consisted of more than 800 individual components, as shown in Figure 2. To reproduce a Jubilee, builders needed to download the project's design files and assembly instructions from Github, fabricate (or find someone else to fabricate) the 3D printed and CNC machined components of the design, and purchase all of the design's off-the-shelf components (aluminum extrusions, fasteners, motion control PCBs, wires, and various electronics components) from over a dozen unique vendors listed in the project's bill of materials, which was formatted as a shopping list spreadsheet. Builders would then follow the project's detailed assembly instructions, which were available in PDF format and included CAD illustrations and written instructions.

Consequently, building a Jubilee took much more time and effort than building a machine from a kit or buying a fully assembled machine. Our interview participants all reported long building times over the course of months, commonly citing shipping times as one of the reasons for the build's duration. P8 noted:

> 'Every time I got stuck was actually due to shipping issues. So once things showed up, the documentation and assembly was quality enough that there was no getting stuck there.'

Our observations show that despite the complexity of the Jubilee project, at least 170 builders successfully self-sourced, assembled, and/or customized Jubilee machines. This number of builders is unusual: many Open Source projects have only one user [9].

JUBILEE PROJECT TIMELINE

DATE	EVENT	DISCORD POPULATION	NUMBER OF JUBILEES
Sep. 2019	V. 1.0 released on Github, Discord server created.	1	0
Oct. 2019	First Jubilee in-the-wild built.	61	3
Nov. 2019		213	10
Dec. 2019		342	18
Jan. 2020	V. 2.0. Laser cut panels group purchase organized by P9.	409	25
Feb. 2020	Wedge plate redesign begins. A vendor sells CNC parts.	506	33
Mar. 2020	V. 2.0.1. UK/EU BOM shared. *Statbot. Begin case study.*	574	34
Apr. 2020	V. 2.0.2.	646	38
May 2020	V. 2.1.0, Wiki created.	731	41
Jun. 2020		810	49
Jul. 2020	V. 2.1.1, new wedge plates for sale. *Participant interviews.*	874	54
Aug. 2020	Klipper config shared by P9	948	63
Sep. 2020	V. 2.1.2.	1026	66
Oct. 2020	#Print-it-forward channel created in Discord.	1084	81
Nov. 2020		1185	87
Dec. 2020	V. 2.2. Jubilee gets Creative Commons 4.0 Int. License	1240	96
Jan. 2021		1313	101
Feb. 2021		1391	109
Mar. 2021		1457	115
Apr. 2021	V. 2.2.1.	1512	126
May 2021		1590	135
Jun. 2021		1646	140
Jul. 2021		1669	143
Aug. 2021		1696	148
Sep. 2021	Lab automation bed plate added to Wiki.	1729	154
Oct. 2021	V. 2.2.2.	1761	158
Nov. 2021		1795	162
Dec. 2021		1823	163
Jan. 2022		1844	168
Feb. 2022	Kit released for sale by vendor. *End of case study.*	1870	170

Table 1 Jubilee Project Timeline. Numbers displayed for Discord population count and estimated tally of Jubilees built in the wild are captured as of the 10th day of each month.

Figure 2 Jubilee's design comprised many separate parts to be sourced and assembled. Shown is a spread of the 800+ components needed for the motion platform (frame) of one Jubilee machine.

3.2 COMMUNICATION WAS A KEY PART OF OVERCOMING SELF-PRODUCTION CHALLENGES

We found extensive evidence that the success of the Jubilee project came not only from an appealing design with an Open Source license, but also from the welcoming online community of people eager to build the project for themselves and assist in the building experiences of others. This community established itself on the *Jubilee Builders and Extenders* Discord server, which became the primary means for builders to engage each other.

We found that Discord's synchronous communication style afforded a very different form of community growth not possible with asynchronous methods of group communication. Unlike a forum or mailing list, the Discord server provided access to information more quickly and more personally. Rather than strictly engaging static project documentation, Jubilee builders were also dynamically engaging each other. We found that questions posted on the Discord, including from newcomers, were often answered within seconds, and data from our statbot confirmed that for the entirety of our case, the server regularly saw message activity at all times of day and night. P3 commented on this activity, noting:

> 'Just the fact that people are on there and able and willing to help out. That's huge. I mean, I'm not able to get on every day and I don't keep it up all the time, but being able to go to the Discord channel as a resource is really useful.'

We observed that although some of our interview participants had already built working Jubilees, they continued to participate on the Discord server because they enjoyed seeing what other community members were sharing. P6 commented:

> 'What really motivates me too is just to share information and kinda see what other people are doing. [...] it's more of just like getting information myself about what people are working on, what kind of neat stuff is out there. You know, so that's a good motivation for me; it's just a good community. A lot of sharing.'

The immediate responsiveness and friendliness of the community, established early by the project's designer and early adopters, was a key element in encouraging new builders to take on the project, facilitating the success of builders whose machines were in progress, and sustaining engagement from builders who had finished their Jubilees.

3.3 COMMUNITY MEMBERS HAD CREATIVE SOLUTIONS FOR SELF-SOURCING PROBLEMS

Builders found self-sourcing components difficult for lots of reasons: the expenses, shipping delays, regional availability of parts, and difficulties in making their own parts were all challenges regularly encountered by Jubilee builders.

We observed that participation in online discussion on Discord manifested into real world actions to overcome these challenges. In October 2020, the community established a *#print-it-forward* channel in the Discord, to organize requests and offers for 3D printing Jubilee components. Additionally, some Jubilee builders on Discord organized group purchasing events to reduce ordering costs among coordinated individual builders. For example, P9 shared:

> 'I wanted to get the laser cut acrylic panels, and I knew a place here in town where I could get them made, but I knew that if I bought one set, it was going to cost me almost as much as it would cost me to make like five sets. So I basically talked to my fiancée and I'm like, okay, you're going to think I'm a little crazy. I'm probably gonna go drop, you know, $400 or $500 for us to have all these acrylic panels made. [...] I'll just post it and see if anybody is interested in group purchasing them with me. And, you know, I basically sold them all.'

Three of our interview participants mentioned that they took part in a group purchase for one or more components.

Furthermore, we observed builders sharing their spare parts to help support other Jubilee builders. P1 mentioned that he had shipped parts to another builder in a different country, explaining:

> 'if you run into a problem as you're collecting all your parts and you need something that'll fit in a flat envelope–easy–I'll do it in a heartbeat.'

In another example of regional help, a community member shared an edited version of the BOM for builders in the UK/EU, with regional alternative vendors to help European Jubilee builders reduce their shipping costs, as Jubilee's original BOM was created for builders in the United States.

Jubilee builders also customized firmware and software to reduce costs for other builders. For example, P9 was interested in introducing capabilities from another Open Source firmware control project, Klipper, to Jubilee. Jubilee's stock design uses Duet3D motion control hardware and RepRapFirmware. He noted:

> 'So when I started looking at that I was like, well, there's gotta be a way to do this without using Duet. So I just happened to run across Klipper around the same time. [...] Immediately I'm like, okay, well, I'm going to build the hardware; I'll work on the electronics.... And, you know, if all else fails, okay, I've wasted $120; I'll go buy a Duet. But if I succeed, then I've just dropped the cost of the printer by several hundred dollars for everybody. So that was kind of my first goal.'

In the months that followed, he did succeed; and he published both a set of configuration files and additions to the Klipper source code online such that others could assemble Jubilee and run Klipper on a substantially cheaper set of electronic control boards. Since P9's instructions, other Jubilee builders have also expanded and built upon his initial work. In the following 2 years we have observed at least 10 other builders bringing up their Jubilee using Klipper on different control boards.

3.4 SELF-PRODUCTION AND COMMUNITY ENGAGEMENT AFFORDED PROJECT IMPROVEMENTS

We found that the work people put into self-sourcing Jubilee parts enabled individual tailoring of builds in a manner quite different from a kit. Rather than purchase a kit, assemble it, and retrofit the finished build with extra tailored components, builders were either purchasing components specific to their custom build or building the project in a piecemeal fashion and tailoring it along the way. Many of these modifications emerged as solicitations for modification advice on Discord and changes during the build process. This mid-build-tailoring was especially true for P4, P2, and P1 who all altered their machines several times in the process of building them before finishing their construction.

P1 explained how he perceived this difference of Jubilee as a *project* versus a *kit*, noting:

> 'When I started looking into the Jubilee project, and I heard somebody [...] explaining to somebody, "Hey guys, this isn't just a kit where you order it and, you know, all the parts are together and, you know, you build it and there's support, right. This is something that we're working on as a community." And so it took me a little while to understand that the advantage of that is obviously just the overwhelming support you get from other people and how much your imagination can just go in any direction in order to adapt to the machine to do what you want it to do.'

We found that this style of project tailoring helped builders feel confident in making modifications going forward. P5 elaborated on this point, saying:

> 'Because the Jubilee is such a versatile tool, people are going to have very different setups. It's just useful to have all this information out there so people can tweak, fix, solve their problems, keep that going, because I don't think there's a single Jubilee out there that people have said, that's it. I'm never going to change anything ever again. It's not the nature of the project.'

Some modifications made and shared by individual builders were eventually folded into the baseline machine design, propelling the design toward more mature and stable versions. One example of this was a community-driven improvement of a component called the wedge plate (shown in Figure 3), which became part of the standard design after its redesign was discussed, modified, and tested by various builders in the online community. The wedge plate is a component included on the back of each tool which enables the tool to securely lock into the machine carriage via the toolchanger mechanism. In the original machine design, the wedge plate was 3D printed, which resulted in stair-stepping surface quality which prevented some tools from being picked up in a repeatable manner from their parked location, a critical requirement for this tool-changing system.

P4 suggested on Discord that the wedge plate be made from a more slippery material, such as Delrin, to mitigate the tool pick up issue, although he did not have the means to test this suggestion himself. Following this suggestion, another Jubilee builder opted to machine a small sample of wedge plates from Delrin and mail these samples to a few interested builders. After tests indicated that these parts were a substantial improvement from the original, various builders indicated their interest in purchasing these parts. The result was that the original designer coordinated a high volume of these parts to be injection molded and made available for purchase by a third party vendor (for $1.99) while adding them to the main project's bill of materials. In his interview, P4 reflected:

> 'And I know that this kind of goes back to the community thing, like, [...] the whole wedge plate thing really is kind of a real community aspect. That is something that took several people all together to make happen. And that is a really big improvement to the project.'

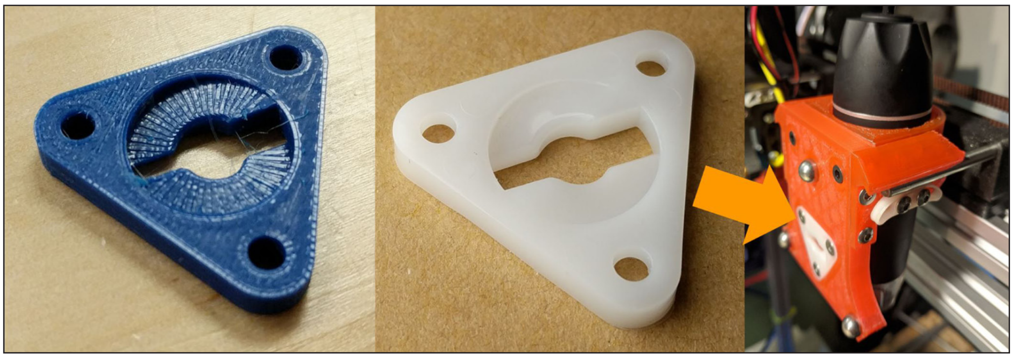

Figure 3 Left: the original 3D printed Wedge Plate. Center: the latest revision of the injection molded Wedge Plate after months of community experimentation. Right: the location of the Wedge Plate on the back of an example tool (a USB microscope). Note that the distinct lack of 'stair-stepping' dramatically improves the reliability of the tool's locking behavior.

We found that while self-production made the Jubilee building process more complex, participants were exceptionally willing to customize and modify their Jubilees after already customizing where and how they ordered their parts. Some of these decentralized discussions and improvements manifested into long-term project improvements which benefited all future builders. After several of these community-driven improvements to the base design occurred over the course of the 30 months following its release, reflected in the version updates shown in Table 1, the Jubilee project achieved a stable enough version that one vendor in the United States released a complete kit of Jubilee frame components for sale on February 10th, 2022. This event marked the end of Jubilee as an exclusively *self-sourced* project, and the beginning of the next chapter of the project's lifespan as one available as an Open Source Hardware *kit*. Builders may now choose between self-sourcing the machine's components (still an attractive option to enthusiastic customizers) or purchasing a Jubilee frame kit all in one box. Both sourcing options still require assembly of the frame and any end effectors.

4 DISCUSSION

In this section, we discuss how themes we observed in the Jubilee case are relevant to other endeavors in the distributed production of Open Hardware. We specifically examine choices made in a project's release and early days, the cultivation of community-driven maintenance and improvements, and gradual legitimization of niche products as infrastructure responds to growth.

4.1 A 'PLUGGABLE COMMUNITY' JUMPSTARTED PROJECT GROWTH

The Jubilee project, as an example of alternative production of Open Source Hardware, owes a lot of its success to the carefully scaffolded and nurtured growth of its vibrant community by the project's designer and earliest adopters.

When Jubilee was initially released, it was pitched to the broader community as a 'multi-tool motion platform.' One major element that drew interest was its extensibility to custom applications. However, to specifically serve the understanding of the community that would build it, Jubilee's design (including its components and geometry) was purposely situated in the ecosystem of existing Open Source 3D printer builders. This concept was akin to Morreale et al's notion of a 'pluggable community' [21]. Jubilee's Discord server is not unique; other Open Source 3D printers such as the Voron, the Railcore, the Blackbox, the Croxy, and the CrazyCreatorCube each have their own Discord servers for discussions related to each of these machines. This notion of leaning on an existing ecosystem of parts and practices was part of what made many elements of the Jubilee project so familiar, and it satisfied Morreale et al's recommendations to keep the barrier to entry low 'with openness to existing tools' [21].

3D printing is not the only use case for Jubilee, and we found examples of Jubilees with no extruder tools at all. However, at this time, multi-material 3D printing is still the most common workflow. This evidence suggests that the Open Source 3D printing community is, by and large, a 'pluggable community' in the case for Jubilee. Here, the capability of multi-material printing by swapping tool heads afforded this existing community with a use case that was presented to fit within their existing hobbyist 3D printing ecosystem. While other novel workflows have emerged, and will likely emerge in the future, this early support and scaffolding from the 3D printer builder community was key to growing the Jubilee community from the project's initial release. Self-produced Open Hardware can have its roots in an existing ecosystem without necessarily being limited to a singular use case for future growth.

4.2 A SENSE OF AGENCY INSPIRES PROJECT MAINTAINERS

Over two years of project vetting, we found that the project improved over time due to the motivation of the community to make it so. We believe that this motivation arose partly from the voluntary and sustained engagement of the project's moderators, maintainers, and individual builders. We observed that the primary Jubilee designer regularly responded to community modifications and incorporated many of them back into the repository while crediting the modifier. As the project grew, some dedicated members of the community contributed their time and expertise to moderating the Discord server. Furthermore, the community as a whole also repeatedly welcomed contributions and discussions related to proposed improvements. The community-created Wiki emerged as a way for individuals not just to navigate project knowledge, but to further add to that knowledge. At least 20 members of the Discord requested editing accounts for the Wiki during our study. We observed that when newcomers could see themselves enacting a process followed by others to produce the hardware, they grew into participants in the project's infrastructure maintenance. By sharing their success, they cultivated both the community and the surrounding support infrastructure that, in turn, reinforced the self-production narrative.

Had the design remained stagnant, unchanging to the modifications presented by builders, or had the community not welcomed suggestions, many design issues would not be addressed. Therefore, we believe that a community's perceived agency, that is, its belief in its ability to influence change in the original project, is key to encouraging community-driven improvements and the general success of an Open Hardware project.

4.3 GRADUAL LEGITIMIZATION REDUCED RISKS AND BOOTSTRAPPED GROWTH

As the Jubilee community grew, a few online vendors began adding various Jubilee-specific components to their inventory such as wire harnesses, springs, motors, and later the injection molded wedge plates. Other vendors began machining Jubilee's hard-to-self-produce aluminum components and offering them for sale. We observed that the availability of pre-made components did not take away from a builder's agency to work directly from the design files, to tailor the components for their build to their liking, or to update their hardware to the most recent version if they wished.

Because producing many of these components for sale involved higher upfront costs and more work for an individual to offer them, they could not have emerged at the very start of the project. This community-driven infrastructural response suggests a workaround to Hodges and Chen's 'challenge of replication', where demand for niche products is too small to merit the overhead required to mass produce the product [14]. Here, over time, Jubilee's design gathered a niche group of people interested in using Jubilee for automated multi-tool applications, and vendors gradually responded.

Concurrent with infrastructural growth, the Jubilee project incorporated numerous hardware changes (geometry changes in the design files, and line item changes in the BOM) as they emerged from community suggestions and issues. These resulted in updated design versions, which occurred as frequently as every month, as illustrated in Table 1. These changes altered the self-production process, making it easier for builders who entered the project in later stages. Had Jubilee been a commercial product, a kit, or a crowd-funding campaign, making design improvements that manifest as changes to real world parts would have been significantly more difficult. In those scenarios, design changes could render a producer's stockpile of specific components obsolete. In contrast, the absence of necessary bulk inventory enabled Jubilee's design to change more frequently in response to community-suggested improvements.

This complementary infrastructural and community growth acted as a form of legitimization of the design driven entirely by a niche community of builders. Rather than through advertising or a crowd-funding campaign, legitimization of the design came from the repeated sharing of successful builds, modifications, and uses of Jubilee through its steadily growing online Discord community, which in turn inspired vendors to further legitimize the design by selling its specialized components. This legitimization speaks to the potential for self-produced Open Hardware projects to bootstrap their own growth.

5 RECOMMENDATIONS FOR SELF-PRODUCED OPEN SOURCE HARDWARE

Based on our research on the Jubilee community, we offer some recommendations for self-produced Open Source Hardware projects.

Firstly, self-production, i.e., a design whose constituent parts can be either purchased off-the-shelf or fabricated with the skills of the target builder, can be an effective strategy to consider for producing hardware. While certainly not applicable to all hardware, a self-produced approach circumvents the immediate need for a large volume production run of specialty components, thereby alleviating some of the constraints placed on the viability of niche or specialty products.

Secondly, we suggest providing and cultivating welcoming spaces for Open Hardware community members to engage with each other, both for social and technical conversations. We found that the online real-time chat interface of Discord promoted conversation and was more newcomer-friendly than Github, forums, or other alternatives. This was reflected in changes to the Jubilee project infrastructure over time.

Finally, we recommend prioritizing community building. We observed that a community that (1) encourages project builders to tailor the project to their needs, (2) helps the in-progress builder complete their build, (3) validates the effort of the builder who has finished building their instance of the project, and (4) is responsive to builder feedback, contributes as much—if not more—to the success of an Open Source Hardware project than the design itself.

6 CONCLUSION

We present an account of the early growing community surrounding the Open Source Hardware project Jubilee. Following the release of the files online, we tracked the community growth on the online Discord server, the builders who chose to self-produce Jubilees, and their collective influence back to the original project. In studying 170+ Jubilee builds in the wild, we found that builders solved for the difficulties of alternative production by organizing group purchases and sharing parts, assisted each other with assembly challenges in real time on Discord, and contributed lasting knowledge via documentation on the project Wiki. Builders openly modified their machines, extended the design's original capabilities, and shared their improvements for the benefit of others. We observed how Jubilee's existence as a *self-produced* Open Source Hardware project enabled it to be readily reproduced and improved, how repeated builds of the machine legitimized the project, and how self-production ultimately drove more flexible, community-driven project improvements that would not have been as readily achievable in mass-produced products. The Jubilee project presents a compelling account of a niche Open Source Hardware project that thrived and succeeded in a distributed manufacturing context.

ACKNOWLEDGEMENTS

Special thanks to Joshua Vasquez, for their brilliant design of the Jubilee project and their open-hearted dialogues with the community of Jubilee builders.

FUNDING INFORMATION

This research is partially funded by the Moore Foundation.

COMPETING INTERESTS

Author NP is the editor-in-chief of the Journal of Open Hardware.

AUTHOR AFFILIATIONS

Kellie Dunn orcid.org/0000-0002-2731-9789
University of Copenhagen, DK; University of Washington, US

Cynthia Feng orcid.org/0000-0002-9510-443X
University of Washington, US

Nadya Peek orcid.org/0000-0001-9405-0399
University of Washington, US

REFERENCES

1. **Albaugh L, McCann J, Yao L, Hudson SE.** *Enabling Personal Computational Handweaving with a Low-Cost Jacquard Loom*. New York, NY, USA: Association for Computing Machinery; 2021. ISBN 9781450380966. DOI: https://doi.org/10.1145/3411764.3445750
2. **Algan Y, Benkler Y, Morell MF, Hergueux J.** Cooperation in a peer production economy experimental evidence from wikipedia. *SSRN*; 2013. DOI: https://doi.org/10.2139/ssrn.2843518
3. **Arduino LLC.** Arduino boards, modules, shields, and kits, 2021. https://www.arduino.cc/, accessed July 2021.
4. **BeagleBoard.** Beagleboard: open-hardware expandable computer, 2021. http://beagleboard.org/, accessed July 2021.
5. **Adrian Bowyer.** Reprap: The self-replicating rapid prototyper, 2021. https://reprap.org/wiki/RepRap, accessed July 2021.
6. **Braun V, Clarke V.** Using thematic analysis in psychology. *Qualitative Research in Psychology*. 2006; 3(2): 77–101. https://www.tandfonline.com/doi/abs/10.1191/1478088706qp063oa. DOI: https://doi.org/10.1191/1478088706qp063oa
7. **Braun V, Clarke V.** Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health*. 2019; 11(4): 589–597. DOI: https://doi.org/10.1080/2159676X.2019.1628806
8. **Buechley L, Hill BM.** Lilypad in the wild: How hardware's long tail is supporting new engineering and design communities. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems*. 2010; DIS '10, page 199–207. New York, NY, USA: Association for Computing Machinery. ISBN 9781450301039. DOI: https://doi.org/10.1145/1858171.1858206
9. **Capiluppi A, Lago P, Morisio M.** Characteristics of open source projects. In *Seventh European Conference on Software Maintenance and Reengineering, 2003. Proceedings.,* 2003; 317–327. DOI: https://doi.org/10.1109/CSMR.2003.1192440
10. **Dasgupta S, Hill BM.** Scratch community blocks: Supporting children as data scientists. In *Proceedings of the 2017 CHI conference on human factors in computing systems*. 2017; 3620–3631. DOI: https://doi.org/10.1145/3025453.3025847
11. **Devendorf L, Ryokai K.** *Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication*. 2015; 2477–2486. New York, NY, USA: Association for Computing Machinery. ISBN 9781450331456. DOI: https://doi.org/10.1145/2702123.2702547
12. **Ducheneaut N.** Socialization in an open source software community: A socio-technical analysis. *Computer Supported Cooperative Work (CSCW)*. 2005; 14(4): 323–368. DOI: https://doi.org/10.1007/s10606-005-9000-1
13. **Herraiz I, Robles G, Amor JJ, Romera T, Barahona JMG.** The processes of joining in global distributed software projects. In *Proceedings of the 2006 International Workshop on Global Software Development for the Practitioner*. 2006; GSD '06, page 27–33. New York, NY, USA: Association for Computing Machinery. ISBN 1595934049. DOI: https://doi.org/10.1145/1138506.1138513

14. **Hodges S, Chen N.** Long tail hardware: Turning device concepts into viable low volume products. *IEEE Pervasive Computing*. Oct 2019; 18(04): 51–59. ISSN 1558-2590. DOI: https://doi.org/10.1109/MPRV.2019.2947966
15. **Hudson SE.** Printing teddy bears: A technique for 3d printing of soft interactive objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014. CHI '14, page 459–468. New York, NY, USA: Association for Computing Machinery. ISBN 9781450324731. doi: 10.1145/2556288.2557338. DOI: https://doi.org/10.1145/2556288.2557338
16. **Khurana R, Hodges S.** *Beyond the Prototype: Understanding the Challenge of Scaling Hardware Device Production*. 2020; 1–11. New York, NY, USA: Association for Computing Machinery. ISBN 9781450367080. DOI: https://doi.org/10.1145/3313831.3376761
17. **Kuznetsov S, Paulos E.** Rise of the expert amateur: Diy projects, communities, and cultures. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*. 2010; NordiCHI '10, page 295–304. New York, NY, USA: Association for Computing Machinery. ISBN 9781605589343. DOI: https://doi.org/10.1145/1868914.1868950
18. **Lakhani KR, Wolf RG.** Why hackers do what they do: Understanding motivation and effort in free/open source software projects; 2003. DOI: https://doi.org/10.2139/ssrn.443040
19. **Li Z, Seering W, Ramos JD, Yang M, Wallace DR.** Why open source?: Exploring the motivations of using an open model for hardware development. Volume 1. *37th Computers and Information in Engineering Conference of International Design Engineering Technical Conferences*; 08 2017. DOI: https://doi.org/10.1115/DETC2017-68195
20. **Lindtner S, Bardzell S, Bardzell J.** Reconstituting the utopian vision of making: Hci after technosolutionism. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2016; CHI '16, page 1390–1402. New York, NY, USA: Association for Computing Machinery. ISBN 9781450333627. DOI: https://doi.org/10.1145/2858036.2858506
21. **Morreale F, Moro G, Chamberlain A, Benford S, McPherson AP.** Building a maker community around an open hardware platform. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017; CHI '17, page 6948–6959. New York, NY, USA: Association for Computing Machinery. ISBN 9781450346559. DOI: https://doi.org/10.1145/3025453.3026056
22. **Oxman N, Laucks J, Kayser M, Duro-Royo J, Gonzales-Uribe C.** Silk pavilion: a case study in fiber-based digital fabrication. In *FABRICATE Conference Proceedings*. 2014; 248–255. ta Verla. DOI: https://doi.org/10.2307/j.ctt1tp3c5w.34
23. **Powell A.** Democratizing production through open source knowledge: from open software to open hardware. *Media, Culture & Society*. 2012; 34(6): 691–708. DOI: https://doi.org/10.1177/0163443712449497
24. **Prusa J.** Prusa research: Open source hardware 3d printers; 2021. https://www.prusa3d.com/, accessed July 2021.
25. **Qi J, Buechley L, Huang Ab, Ng P, Cross S, Paradiso JA.** Chibitronics in the wild: Engaging new communities in creating technology with paper electronics. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018; CHI '18, page 1–11. New York, NY, USA: Association for Computing Machinery. ISBN 9781450356206. DOI: https://doi.org/10.1145/3173574.3173826
26. **Rivera ML, Hudson SE.** *Desktop Electrospinning: A Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles*. 2019; 1–12. New York, NY, USA: Association for Computing Machinery. ISBN 9781450359702. DOI: https://doi.org/10.1145/3290605.3300434
27. **Saldaña J.** The coding manual for qualitative researchers; 2021.
28. **Sells E, Bailard S, Smith Z, Bowyer A, Olliver V.** *RepRap: The Replicating Rapid Prototyper: Maximizing Customizability by Breeding the Means of Production*. 2010; 568–580. DOI: https://doi.org/10.1142/9789814280280
29. **Takahashi H, Miyashita H.** *Expressive Fused Deposition Modeling by Controlling Extruder Height and Extrusion Amount*. 2017; 5065–5074. New York, NY, USA: Association for Computing Machinery. ISBN 9781450346559. DOI: https://doi.org/10.1145/3025453.3025933
30. **TeBlunthuis N, Shaw A, Hill BM.** Revisiting "the rise and decline" in a population of peer production projects. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018; CHI '18, page 1–7. New York, NY, USA: Association for Computing Machinery. ISBN 9781450356206. DOI: https://doi.org/10.1145/3173574.3173929
31. **Teibrich A, Mueller S, Guimbretière F, Kovacs R, Neubert S, Baudisch P.** Patching physical objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. 2015; UIST '15, page 83–91. New York, NY, USA: Association for Computing Machinery. ISBN 9781450337793. DOI: https://doi.org/10.1145/2807442.2807467
32. **Tseng T, Resnick M.** Product versus process: Representing and appropriating diy projects online. In *Proceedings of the 2014 Conference on Designing Interactive Systems*. 2014; DIS '14, page 425–428. New York, NY, USA: Association for Computing Machinery. ISBN 9781450329026. DOI: https://doi.org/10.1145/2598510.2598540

33. **Ultimaker BV.** Ultimaker 3d printers; 2021. https://ultimaker.com/3d-printers, accessed July 2021.
34. **van der Zalm E.** Marlin firmware; 2021. https://marlinfw.org/, accessed 2021.
35. **Vasquez J, Twigg-Smith H, O'Leary JT, Peek N.** Jubilee: An extensible machine for multi-tool fabrication. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020; CHI '20, page 1–13. New York, NY, USA: Association for Computing Machinery. ISBN 9781450367080. DOI: https://doi.org/10.1145/3313831.3376425
36. **Wang G, Yao L, Wang W, Ou J, Cheng C-Y, Ishii H.** Xprint: A modularized liquid printer for smart materials deposition. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2016; CHI '16, page 5743–5752. New York, NY, USA: Association for Computing Machinery. ISBN 9781450333627. DOI: https://doi.org/10.1145/2858036.2858281

TO CITE THIS ARTICLE:
Dunn K, Feng C, Peek N. 2023. Jubilee: A Case Study of Distributed Manufacturing in an Open Source Hardware Project. *Journal of Open Hardware*, 7(1): 4, pp. 1–15. DOI: https://doi.org/10.5334/joh.51

Published: 05 May 2023