

ISSUES IN OPEN HARDWARE

Critical Factors for Implementing Open Source Hardware in a Crisis: Lessons Learned from the COVID-19 Pandemic

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The rapid spread of COVID-19 has created an urgent demand for critical items including clinical care equipment and protective personal equipment. The failure of traditional industry to meet this demand has led to a huge response from the maker community, who are rapidly mobilising to produce Open Source Hardware (OSH) solutions. Community-driven, distributed manufacturing is enabling production on a global scale never seen before. In this paper, we focus on sensemaking as a process by which meaning is given to collective experiences. We identify six case studies of OSH projects responding to the COVID-19 pandemic, and report on their activities between March–June 2020. In doing so, we uncover several novel collaborations that are emerging between the informal maker community and other formal institutions, including research institutions, non-government organisations and incumbent manufacturers. By observing and reflecting upon these experiences, we identify potential critical factors for implementing OSH in a crisis. We highlight the importance of establishing legitimacy and community management, as well as the enabling conditions in the ecosystem that make OSH more favourable. These findings have implications for various actors beyond the Maker community. In conclusion, we suggest several promising areas for further research. In particular, we believe that this initial study of OSH during the COVID-19 provides a foundation for further longitudinal studies of OSH in a crisis.

Keywords: Open Source; Open Source Hardware; crisis; humanitarian; success

1. Introduction

The rapid spread of COVID-19 has led to a global shortfall in medical supplies (Chagas et al. 2020). An unprecedented demand for essential items, coupled with global supply chain disruption, has resulted in widespread shortages (López-Gómez et al. 2020). The failure of traditional industry to meet this demand has given rise to self-organising networks of makers that are mobilising rapidly via peer to peer networks (Corsini et al. 2020). Across the world, these communities of makers are producing critical items to tackle the spread and treatment of COVID-19.

This large-scale response from the global maker community is partly enabled by Open Source Hardware (OSH), which allows designs to be freely accessible so that anyone can use and modify them (Pearce 2017). Makers have a longstanding tradition of using digital fabrication tools (e.g. 3D printing, laser cutting and CNC milling) to locally replicate, adapt and customise digital design files that are shared via the internet using open source repositories such as GitHub (Corsini, Aranda-Jan, and Moultrie 2019; Corsini and Moultrie 2019). In this way, makers globally are able to cooperate and form connected, open and decentralised communities. When oriented towards a

common goal, these communities can constitute a distributed manufacturing network (Pearce 2020).

According to the World Health Organisation, critical items can be categorised as: (i) Personal Protective Equipment (PPE), (ii) Diagnostics equipment; or (iii) Clinical Care Equipment (World Health Organisation 2020). **Table 1** highlights a range of typical OSH projects across each of these categories, including nasal swabs, face masks, face shields, and ventilators. Although this is not the first time that makers have helped to produce essential items in a crisis (Loubani 2018; Britton 2018; Corsini and Moultrie 2020; Corsini, Aranda-Jan, and Moultrie 2020), the early stages of the coronavirus pandemic led to a response from the maker community on an unprecedented scale. Whereas prior to the COVID-19 pandemic, makers have been largely viewed by mainstream industry as “hobbyists” who spend their time “tinkering” (Peppler, Halverson, and Kafai 2016), this crisis has seen urgent requests for medical items being sent to “anyone with a 3D printer” via WhatsApp and other social media (see **Figure 1**). ‘Open Source COVID19 Medical Supplies’, a global open source community that is organised on Facebook, claims that over 12 million items have been produced since 28th March 2020 by their group alone (‘Open Source COVID19 Medical Supplies’ 2020).

In this quickly unfolding crisis, there has been little opportunity for sensemaking among the OSH community.

Table 1: Examples of Open Source Hardware projects to develop critical items for COVID-19.

WHO list of critical items for COVID-19	Open Source Hardware projects
Personal Protective Equipment (PPE)	Surgical masks (Richburg 2020; Copper 3D 2020) Particulate respirator masks (Czech Institute of Informatics, Robotics and Cybernetics 2020) Face shields (HappyShield 2020; Prusa Research 2020; Field Ready: Erbil Makerspace 2020) Protective gowns (For The Love Of Scrubs 2020; ScrubHub 2020) Protective goggles (Field Ready 2020)
Diagnostics equipment	CPAP ventilators (OxVent 2020; VentilAid 2020; MIT E-Vent 2020) Ventilators (OVSI 2020)
Clinical Care Equipment	Nasal swabs (Formlabs 2020) Lab screening test kits (JOGL 2020)

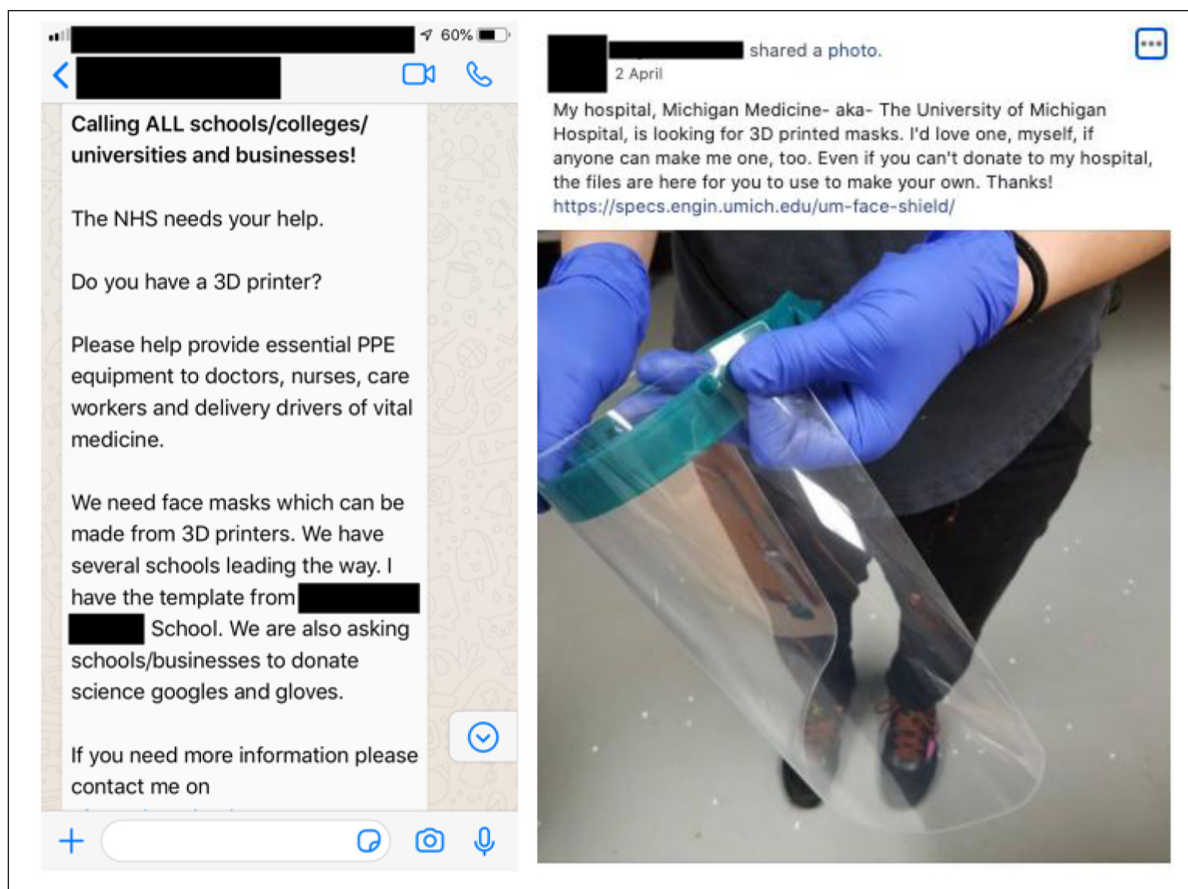


Figure 1: Requests for makers to respond to shortages of critical items via social media. Source: First Author's WhatsApp (Left), Open Source COVID19 Medical Supplies Facebook Group (Right).

It is well-accepted that sensemaking is an important activity for giving meaning to collective experiences and that it can help to shape a field (Weick, Sutcliffe, and Obstfeld 2005). This paper contributes to knowledge by providing an update on OSH solutions being developed by distributed maker communities. It is among one of the first studies to analyse these efforts, and to reflect on the lessons learned so far. By selecting prominent case studies of OSH interventions during the early stages of the pandemic, we aim to help document the role of OSH in a crisis and to identify critical factors for its implementation. First, we explain our methods for cross-case analysis. Second, we describe each of the main case studies. Third, we present critical factors for implementing OSH in a crisis. Finally, in

our discussion, we reflect on the underpinning theories which might be relevant for future research and we suggest possible elaborations to this study.

2. Method

As there is a large and growing number of maker responses to the COVID-19 crisis (COVID-19-Solutions 2020), we began by purposefully sampling maker initiatives, focusing on a small number of revelatory case studies that reflect best practice (Palinkas et al. 2015). Case studies are a popular way of dealing with real-life phenomena that are difficult to separate from the context of study (Yin 2018). An initial search for case studies was conducted between 1st–8th April, and a series of inclusion criteria was

developed. First, case studies should be OSH solutions developed by the maker community to tackle COVID-19. Second, the case studies should represent a range of products, from low complexity items (e.g. PPE) to high-complexity items (e.g. clinical care equipment). Third, we wanted to select projects that had been implemented or were reportedly very close to implementation. With these criteria in mind we paid close attention to cases that had received widespread acclaim in the press. Finally, we wanted cases that collectively represented a diversity of geographical regions from the Global North and South. **Table 2** presents a summary of the case studies included in this study.

Both primary and secondary data were collected in order to build up a detailed understanding of the cases. This included reviewing websites, press, design repositories, videos, social media and Slack channels. This secondary data helped the researchers to build up an understanding of the case studies, identify the key actors involved and develop a timeline of events. This data is integrated into the description of the case studies in Section 3. This information also helped to guide the semi-structured interviews, which were conducted with project members between 8th–28th April 2020.

Interviews have been well-used in other qualitative studies of Open Design projects (Menendez-Blanco and Bjørn 2019; Dew et al. 2019), and they have also been used by similar studies to complement the retrieval of information from reports and observations (Freeman, Bardzell, and Bardzell 2019). In total, seven interviews were completed by phone/Skype/Zoom lasting between 25–60

minutes, with one interview completed by email (see **Table 2** for interviewee details). The interviews covered a range of topics including: project motivations, actors' activities and contributions, project enablers and main challenges faced. The interviews aimed to uncover all the possible factors that helped the projects to progress from idea to implementation. All the interviews were recorded with the participants' consent and complemented with detailed note-taking.

The interview recordings were transcribed verbatim and imported to MAXQDA for analysis. Following recommendations by Saldaña (2015) line by line thematic coding was conducted to identify the critical factors that supported the development and implementation of their OSH projects. Initially, this resulted in 33 codes. These codes were then further refined and grouped in a second round of pattern coding (ibid), which aims to identify relationships between codes. After several rounds of organising these codes, the factors were categorised resulting in three codes and nine sub-codes. The main data analysis and writing of this manuscript was completed in June 2020. This paper reports on the activities of the case studies between March-June 2020.

3. Case studies

3.1 3D Crowd UK

3D Crowd UK is a volunteer-based initiative that was set up at the end of March 2020 to manage the demand and supply of 3D printed PPE in the UK. It began as a local operation to coordinate orders for 3D printed face shields in Yorkshire, and quickly expanded across the UK (3D

Table 2: Summary of the case studies.

Project	Product type	Key Organisations	Region	Project status	Interviewee Details
1 3D CrowdUK	Face shields	3D CrowdUK, Prusa	UK	>160,000 face shields delivered to 90+ NHS trusts	Marketing manager, 3D Crowd UK (01-01)
2 M19 Collective	Face shields	Maker's Asylum	India	392,636 face shields to clinicians and front-line workers	Co-founder, Maker's Asylum (02-01)
3 "FabLab Philippines COVID response"	Face shields, aerosol boxes, PPE, face masks	FabLab Phillipines Network, Field Ready	The Philip-pines	66,500 face shields, 276 aerosol boxes, 16 disinfecting stations, 1,300 PPE gowns, 31,000 face masks	Programme Manager, Field Ready (03-01)
4 Easy COVID 19	CPAP* ventila-tor mask	Isinnova	Italy	1000+ masks have been distributed to 50+ hospitals in Italy. 2.5 million downloads of their design.	CEO, Isinnova (04-02), Engineer, Isinnova (04-02)
5 Open Source Ventilator (OSV) Ireland	Emergency (CPAP*) ventila-tor	OSV Ireland, Ford, Amazon	Ireland	Ventilator is in development and testing in Ireland. Global community of over 2,500 volunteers.	Co-founder, OSV Ireland (05-01)
6 OxyGEN	Emergency (CPAP*) ventila-tor	Protofy.xyz	Spain	Ventilator has received the approval of the AEMPS (Spanish Agency for Medicines and Health Products) to start its use on patients at all hospitals that adhere to the clinical study. 150+ local chapters develop-ing OxyGEN around the world.	Co-founder, Protofy. xyz (06-01)

* Continuous Positive Airway Pressure.

Crowd UK 2020c). The 3D Crowd platform enables both front line workers to request face shields online, and hobbyists with 3D printers to register as volunteers.

All volunteers are requested to manufacture identical 3D printed face shields using the open source RC Prusa design, which is verified by the Czech Ministry of Health. Volunteers are also limited to use only PLA or PETG for the headband (3D Crowd UK 2020c). The decision to standardise production, using one of the first face shields to be approved by a national health department, enabled the network to maintain distributed quality control and quickly build credibility via the success of Prusa's face shield.

Coordination efforts were emergent but effective. The group uses Slack and its channels to share updates, ideas, questions and support (3D Crowd UK 2020a). 3D Crowd also has Standard Operating Procedures (SOPs) for makers and hubs to ensure it meets the criteria set out by the UK Office for Product and Safety Standards. All of the SOPs are available on 3D Crowd's website (3D Crowd UK 2020b) and it is mandatory for all volunteers to read the SOPs. Once registered, makers receive instructions for how to 3D print the headbands for the face shields, seal them and book a collection slot. DPD, a courier service, transports these printed parts free of charge to local hubs. After final assembly and quality checks are completed, the face shields are distributed to end users.

So far, 168,000 face shields have been made out of 600,000 face shields requested. In one week alone, 3D Crowd UK delivered 39,000 face shields to 90 NHS Trusts and care homes (3D Crowd UK 2020a). Crowdfunding for the campaign has raised over £150,000 (Go fund me 2020). After 3 days of launching the crowdsourcing campaign, the network were able to raise £10,000 which crucially enabled them to scale from locally producing and supplying PPE to setting up centralised hubs for distribution. As of May 2020, 3D Crowd has a CE mark application in process, and British Standards Institute is aware that the design is currently being used by health workers (3D Crowd UK 2020d).

3.2 M-19 Collective

M-19 is a collective of 42 organisations in India that have formed a distributed manufacturing network to locally produce and distribute over a million face shields to front line workers in India. The project began when the co-founders of Maker's Asylum, a makerspace in Mumbai, began prototyping face shields by hand and posting videos online at the end of March 2020. Within 48 hours they received their first requests for face shields from healthcare workers. At that time, face shields were extremely scarce in India, and those that were available were prohibitively expensive. By locally manufacturing face shields, they were able to produce face shields for less than \$1 (Maker's Asylum 2020a).

Maker's Asylum began publishing their designs online, as well as experimenting with 3D printing and laser cutting to scale-up production. As word of mouth spread, requests from local hospitals increased rapidly. Initially

they began loosely collaborating with a few other maker-spaces, but after setting a target of producing 10,000 face shields, they realised that a more structured and collective effort was needed. Maker's Asylum conceived of the M-19 Collective as a way to unify the efforts of local and distributing groups in India who were producing face shields. This collective did not mandate a single design or production technology, as individual organisations were free to adapt their designs according to local needs and constraints. Since the initiative started, Maker's Asylum have developed over 21 different design iterations (Maker's Asylum 2020b).

Initially the first face shields were produced using acrylic for the headband, however as shortages of acrylic and PET became more widespread, the network turned to readily available materials that you could find in an ordinary stationary shop. Instead of acrylic, they used foamboards. Instead of PET sheets, they use Overhead Projector (OHP) sheets for the visors. As each organisation in the M-19 collective encountered their own supply chain challenges, they adapted the designs to accommodate available materials. They also collaborated to pool resources and to share information about how to procure materials.

By acting quickly, at a time when there were no alternatives available, the M-19 collective were able to gain the trust of healthcare practitioners. This also led to high profile endorsements from government ministers and national press which further helped to build the legitimacy of the initiative. New groups joining the collective were able to leverage this profile, and build credibility locally by demonstrating the impact of the network already in other regions.

3.3 FabLab Philippines COVID-19 Response

In the Philippines, a consortium of 40 FabLabs have been collaborating to produce critical items for the COVID-19 pandemic. For the past few years, FabLabs in the Philippines have been regularly convening at a national conference called Fab Fest (Field Ready 2019). Within the Philippines, the FabLab network is also well supported at an institutional level by the government, with most of the fabrication spaces embedded in a higher education research institution (Lontoc 2018).

So far, the FabLab Philippines network has produced 65,000 face shields, 276 aerosol boxes, 16 disinfecting stations, 1300 PPE gowns and 31,000 face masks. This achievement has been made possible by the development of strong collaborations between makers, medical experts and practitioners, as well as academic researchers. The Department of Trade and the Chambers of Commerce have also been closely supporting the Fablabs to source the materials needed, and to provide the necessary permissions for the Fablabs to remain open.

In some cases, FabLabs have been pooling resources to effectively distribute supplies. Local businesses have also been forthcoming with donations of food and equipment. In addition, Field Ready, a Non-Governmental Organisation, has helped to coordinate and share knowledge between their national and international network. At

the heart of this consortium lies an ethos of collaboration that is centred around the Filipino concept of *Bayanihan* or “communal unity”.

3.4 Easy COVID19

Isinnova were among the first group of makers to receive widespread publicity for 3D printing life-saving valves for ventilators. After a hospital in Brescia discovered that the manufacturer of ventilators would not be able to supply spare parts for several weeks, they contacted the local newspaper with an urgent request for help (Kleinman 2020). Before publishing an advert, the editor of the newspaper contacted a maker who put them in touch with Isinnova. This serendipity, or social capital, meant that within less than 24 hours, Isinnova were able to design, print and distribute over 100 ventilator valves. According to them, this could have been possible only in an extreme crisis: normally regulatory approvals in Italy take more than 18 months.

After news of this ground-breaking project spread around the world (Feldman 2020), a retired clinician, Renato Favero, contacted Isinnova about an idea to develop a low-cost ventilator mask, which he predicted hospitals would soon need urgently (George 2020). In this case, their initial success helped to build their credibility. Isinnova began working with Favero and clinicians from a local hospital in Brescia to repurpose a Decathlon scuba diving mask, using 3D printing. The team contacted Decathlon, who provided the design files of the scuba mask for the team to design a solution. Within ten hours of receiving the files, they had designed and 3D printed a ‘Charlotte valve’, an attachment that could convert a scuba diving mask into a fully functional mask for Continuous Positive Airway Pressure (CPAP) ventilation.

After initially validating the device at a local hospital, the team decided to immediately patent it and openly share it. To do this, they sought Intellectual Property advice from legal consultants. By this time, it had already been widely misreported that the team were being sued by the original manufacturer of the ventilator valves, which they developed as part of their first COVID-19 project (Kent 2020). By the end of April 2020, there were over 2.5 million downloads of these designs worldwide. Over 1000 masks have been distributed to over 50 hospitals in Italy. They are now collaborating with incumbent manufacturers to injection mould these parts.

3.5 Open Source Ventilator (OSV) Ireland

This initiative was born out of discussions on a Facebook group on Open Source COVID19 Medical Supplies (OSMS). OSV Ireland was formed by Colin Keogh, Conall Lavery and David Pollard, who were initially involved in the promotion of the OSMS Facebook group but as it grew rapidly to over 20,000 members, they realised a more focused and localised effort was needed. They formed OSV Ireland with the goal of developing an emergency ventilator to support the Irish Health Service. The core team’s prior experience working with the Irish Health Service helped them to quickly mobilise and to build credibility. In addition, their

affiliation with University College Dublin allowed them to access prototyping workshops.

At present, OSV Ireland has a global community of over 2500 members who work collaboratively online using Slack and GitLab to share and develop their designs (Open Source Ventilator 2020). The project received widespread acclaim after being hailed the first low-cost open source ventilator to be ready for testing “in just one week” (Etherington 2020). This publicity helped them to galvanise support from volunteers, as well as attracting interest from incumbent manufacturers. OSV Ireland has established collaborations with Ford, to support with Design for Manufacture, and Amazon to assist with logistics and distribution. As of May 2020, their device is under development and testing. All of the designs are openly available via their website and GitLab (OpenLung Emergency Ventilator 2020).

3.6 OxyGEN

This project was initiated by Protofy.xyz, a Spanish rapid prototyping start-up. As images of overwhelmed hospitals in Italy started being widely shared in March 2020, Protofy.xyz realised that the global shortage of ventilators would soon become a critical issue. They established a multidisciplinary group of professionals and makers that are focused on developing two versions of an emergency ventilator: one for production by industry (OxyGEN IP), and one for production by makers (OxyGEN M). OxyGEN M was designed to be built using locally available materials such as acrylic or wood, and using production tools readily available in community fabrication spaces e.g. handsaws or CNC machines (OxyGEN 2020b). OxyGEN IP was designed to be manufactured using intensive machining tools and targeted at professional organisations, manufacturers and research institutions (ibid). This version in Spain received approval to be used in clinical trials (IGTP 2020).

In Spain, OxyGEN has benefited from strong support from civil society, small and large corporations, and government institutions including the Ministry of Health and Ministry of Justice. From the very beginning, OxyGEN started working with two main hospitals in Barcelona: Hospital Clínic and Hospital Germans Trias i Pujol. By working closely with the hospitals, they have been developing a device ‘designed by and for doctors’. As well as developing a core team based in Barcelona, OxyGEN has benefited from engaging with a global open hardware community. Around the world, over 150 maker communities have established local chapters to replicate and develop the ventilator (OxyGEN 2020a). The project has had over 80,000 views and more than 16 design iterations have been developed (OxyGEN 2020b).

By adopting this open approach, OxyGEN believes that they were able to benefit from very fast and qualified feedback from the community, as well as attracting interest from incumbent manufacturers. For example, Volkswagen Group reached out to OxyGEN after initial reports of their success, and SEAT have been supporting them with Design for Manufacture and testing of the ventilator (SEAT 2020).

OxyGEN also reports that they have collaborated with over 110 companies (OxyGEN 2020b). These collaborations were critical for product development, testing and dealing with regulatory certifications.

4. Findings

Based on our analysis of the case studies presented above, we identify critical factors for implementing OSH in a crisis. At the project-level, critical factors include the development of project **legitimacy** and **community management**; at the ecosystem level, we uncover **enabling conditions** that are key to implementing OSH in a crisis. **Figure 2** provides an overview of these project-based and ecosystem factors, and their related themes. **Figure 3** highlights the reciprocal relationship between project-based factors. That is to say that effective community management helps to reinforce legitimacy, which in turn enables better management of communities. It also draws attention to how ecosystem factors influence the project-level, through the existence of enabling conditions which make OSH more favourable.

4.1 Legitimacy

Building legitimacy emerges as a critical factor for implementing OSH in a crisis. In normal times, the practices of the maker community are often conceptualised as “non-professional” (Browder, Aldrich, and Bradley 2019). More specifically, it can be said that OSH often lacks legitimacy i.e. it suffers from a general perception that it is not “desirable, proper or appropriate within ... [the] system of norms” (Suchman 1995).

Among the case studies, we discover three key strategies that help to build legitimacy. First, acting quickly and thinking frugally was important to developing credibility. For instance, Isinnova’s quick response to printing ventilator valves in a moment of crisis helped to establish themselves as a trusted partner for clinicians. Their initial success led to a request for their help to develop another project to produce ventilator masks.

He read an article about our idea to print the valve and he called us and said, “I think that in a few days probably some hospitals will need respiratory masks but we do not have enough, so can you help me to convert a snorkelling mask into a respiratory one?” I said, “Okay, I will help. Give me the medical information and I’ll try to create it.” So we collaborated to create the Charlotte valve together. (04-01)

Second, projects that responded quickly were also able to attract significant media attention at the start of the crisis and further use this to establish legitimacy. By going very loud and public early on, many of the projects were able to mobilise volunteer networks, crowdsource funding and secure the partnerships they needed to develop and implement solutions. For example, OSV Ireland received widespread coverage as one of the first OSH ventilators (Etherington 2020) which helped them to secure partnerships with incumbents, such as Ford and Amazon.

If you’re going to start an initiative you have to go very public and loud at the beginning. And the reason that we decided to do that is because it gets you the partners you need... So going very loud and very public in the first week was by design to make sure everyone knew what we were doing and then we could get the partners we need. And it’s worked. (05-01)

The media has swept it along... PPE is constantly in the news ... it’s a network effect. (01-01)

Third, multi-actor collaborations help to improve the reputation of OSH projects. In all the cases, we observe novel collaborations emerging between informal networks of makers and other formal institutions, such as research institutions, governments, health services and existing industry. Not only did these collaborations facilitate knowledge exchange and help to coordinate supply and demand, they also strengthened the institutional

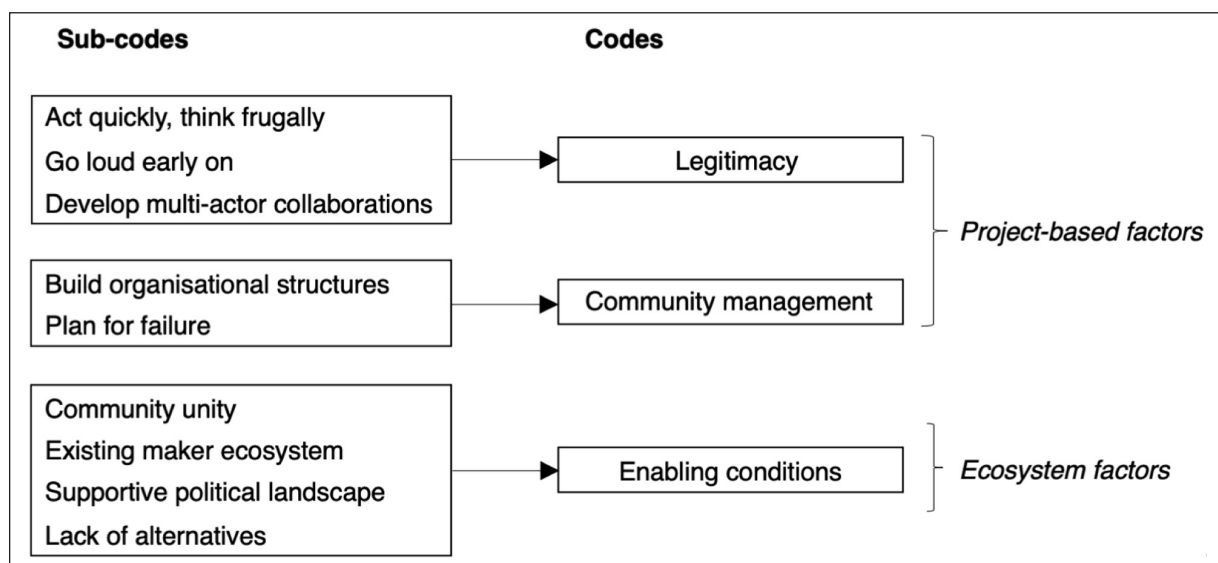


Figure 2: Critical factors for implementing OSH in a crisis.

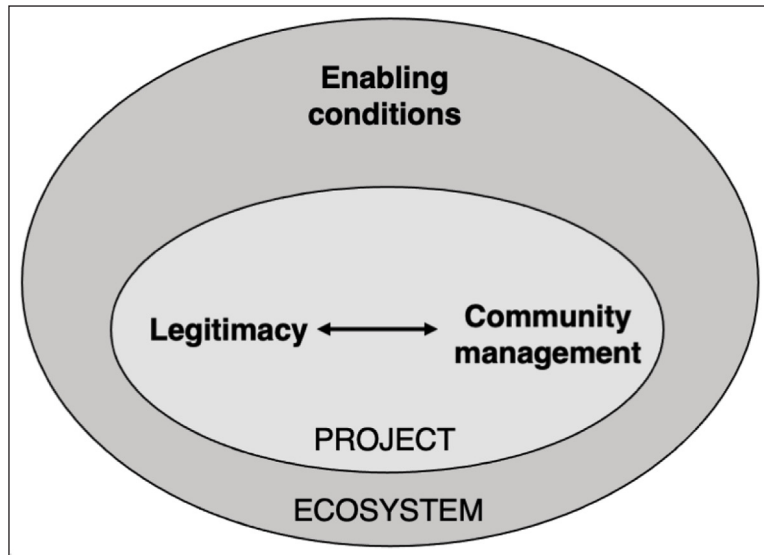


Figure 3: Relationships between critical factors for implementing OSH in a crisis.

capital of OSH projects. In particular, support from formal institutions, such as universities and government departments, allowed the makers to access essential workshops and fabrication spaces. Early endorsements from these formal institutions were also pivotal in helping to further build reputation and attracting collaborations. As OSH projects spread to new locations, new chapters were able to quickly establish legitimacy under the central ‘brand’ of the project.

What we're trying to do is just combine the initiative of all of the labs to go out with one voice. The fact that all these smaller hubs across the country can take whichever design works... we can have bigger impact as a collective. (02-01)

The open hardware approach allowed very fast and qualified feedback of a huge community. This brings also the third factor that OxyGEN is a global solution from the beginning, thanks to the open hardware approach. And the last thing the open hardware approach gave to the project is great partnerships. As many big companies have been looking for solutions, Volkswagen Group came to us to use our solution. (06-01)

4.2 Community management

The surge in volunteer support at the start of the crisis led to noisy platforms that were difficult to organise. It is notable that all of the case studies focused initially on local coordination as a key strategy. Groups leveraged their own social capital within their local networks, and used this as a foundation to broaden their outlook to other contexts.

Me and a couple of other people around in Ireland said, “Look, we can have a more focused effort here. We know each other, we know the position, we know people in the health service, we know everything we need in this country. So we can be a little bit leaner on how we operate compared to this huge group.” (05-01)

Our findings highlight an inherent tension between the ethos of collaboration and openness in OSH, and the need for effective organisational structures. Many of the case studies dealt with this challenge by using a partially self-organising approach. For instance, OSV Ireland coordinates the large-scale distributed development of their ventilator mainly using the communication platform Slack. However they have identified local leaders and coordinating actors were identified to help manage distributed teams. Taking a different approach, OxyGEN streamlined the development of their ventilator mainly through local coordination with strong support from local government and hospitals. There are now over 150 chapters of OxyGEN across the world, which operate as independent chapters.

Another key finding from the case studies is that long-term planning is key to implementing OSH in a crisis. OSH projects should prepare for volunteer support to diminish after the immediate crisis response phase. As a result, significant efforts must be invested into proper documentation of what works, what doesn’t work and why. This goes much further than just the open sharing of final designs, and it is critical to avoid redundancy in the long-term. By planning for failure, OSH projects can strive to do the opposite.

I fully expect that if the peak is this week or next week all of that is going to disappear... an awful lot of the drive to solve the problem will evaporate... But that’s the important stage. What happens then, how do you get these projects over the line? And that’s why we think our open source approach is the way to go because even if all of that disappears... all of our information is online... you can see the failed designs, you can see the failed revisions. There’s notes in there on why they failed... with some other teams if it’s not successful, it won’t be open. (05-01)

4.3 Enabling conditions

As well as building legitimacy and community management, our findings suggest that certain enabling conditions make implementing OSH in a crisis more favourable.

First, it goes without saying that many of OSH solutions in this study would not have been accepted were it not for the unique circumstances that the COVID-19 pandemic brought about. The shared urgency of the crisis helped to build a common understanding of the benefits of OSH. At the same time, the shortage of conventional solutions created a window of opportunity for OSH. The implication is that community-driven OSH should in the first instance seek to exploit gaps in the traditional manufacturing system, instead of directly competing with it.

When we went to a hospital, a doctor told us, "If I have to leave a patient without oxygen or try to treat him with a 3D printed part, what do you think I will do? Of course, I will try to do whatever I can to try to help him." (04-01)

Second, the case studies emphasise the importance of an enabling maker community that helped to rapidly mobilise. Without this existing infrastructure the projects would simply not have been possible.

"The open hardware approach allowed very fast and qualified feedback of a huge community." (06-01)
"It's the network effect... I had no idea there were so many people with 3D printers out there to be honest." (01-01)
"While they [incumbents] can be really focused with their work they cannot go through the volume of iterations that this open source maker group can." (05-01)

In addition, these findings also speak more broadly to the role that communal work (i.e. a shared vision and sense of belonging) can play in successful OSH projects. It is not enough to collaborate, but a common ethos and way of working must also be established. In the context of the Philippines, it is clear that a cultural precondition for collaboration existed in the popular concept of 'communal unity'. Specifically, this helped to deal with the challenge of material shortages by helping to pool supplies.

All the maker community and the people that know the FabLab and have been using the FabLab have been offering the things that they have. Like even a roll of acetate, acrylic sheets, 3D printing filaments. Some FabLabs that are not responding are giving their materials to the labs that are responding. We call it in our language Bayanihan, which is a communal unity. (03-01)

Finally, this study points out the importance of a supportive political landscape. The findings suggest that greater formal recognition of the OSH community and understanding of its contributions helps to accelerate impact. Specifically, in the COVID-19 crisis, early recognition that makerspaces and fabrication spaces were part of 'critical infrastructure' would have helped to overcome workshop restrictions that caused delays to progress. In the case of

the FabLab Philippines' COVID-19 response, the close relationship between the FabLabs and government enabled the sharing of resources and distribution of critical items to front-line workers. This strong institutional support also helped to navigate the approvals process and grant regulatory exemptions. These findings signal the importance of complementary top-down approaches to enable bottom-up OSH solutions.

The relationship with the Fab Labs with the government, especially with the Department of Trade and Industry, it's so tight that the government is actually helping each lab to source materials. (03-01)

5. Discussion

This study has created an opportunity for sensemaking by shedding light on OSH responses to COVID-19. By analysing six cases, we have identified critical factors when implementing OSH in a crisis. First, we identified the need for OSH projects to build legitimacy and effective community management. Second, we highlighted enabling conditions that make OSH more favourable in a crisis. To this extent, we argue that implementing OSH necessitates the collaborative efforts of actors beyond the maker community.

The findings in this study echo calls for a shift away from the "heroic innovator to distributed heroism" (Meijer 2014). In all the case studies, heterogenous networks of actors collaborate throughout the product development process to leverage various resources. Rather than viewing the flourishing of OSH responses during the COVID-19 pandemic as a spontaneous occurrence, these activities should be seen as the result of ongoing maturation of the maker community. What this means is that long-term investments in these capabilities will ultimately pay off (López-Gómez et al. 2020). We also critique technosolutionist views that fail to view makerspaces within a broader socio-political context (as in Lindtner, Bardzell, and Bardzell, 2016). In this pandemic, it is clear that makerspaces are still part of a global value chain, which is subject to supply chain disruption.

Recognising these community fabrication spaces as part of a wider manufacturing ecosystem further underlines the need for support from actors beyond the maker community for OSH to thrive. Although informal relationships have existed for some time between makers and public institutions, this study shines a light on the particularly novel relationships unfolding between the maker community and incumbent manufacturers. It sets a precedent for how future crisis responses might be organised. Contrary to the open innovation literature on asymmetric partnerships between start-ups and large firms (Minshall et al. 2015), we discovered that collaborations between makers and incumbents were effective and synergetic. We speculate that this might be because these projects sit outside of the scope of incumbents' normal commercial activities. In the cases reviewed, various actors were driven by a shared commitment to tackling COVID-19 and were highly motivated by the perceived urgency of the

crisis. We thus question: is this a one-off or will we see an increase in collaborations between makers and incumbents in the future?

We also question the extent to which the reputation building of OSH during the pandemic will continue once the crisis 'ends'. Although previously marginalised as a hobbyist activity, we have witnessed OSH being called upon and widely celebrated for its contributions during the pandemic (Kleinman 2020). Specifically, our study highlighted how legitimacy was built in three main ways: (1) by quickly addressing an unmet need; (2) through gaining widespread publicity; (3) by developing partnerships with trusted players. It remains to be seen whether the effects of this increased legitimacy will be long-lasting or whether when the pressing urgency for critical items subsides, the maker community will resume a 'non-professional' identity. We call for future research to investigate how the response to COVID-19 pandemic has changed perceptions towards the maker community, and to what extent this will enable a transition towards the increased adoption of OSH.

Finally, we reflect on our findings to call for more diverse perspectives on global making. As Lindtner, Bardzell, and Bardzell (2016) points out, prior research has largely focused on Western technocratic perspectives of making. Whilst the Maker movement is "often presented as a global universal" it is better understood through assemblages of related activities. Future research could further explore the enabling potential of different community practices beyond those that predominate in Eurocentric studies of the maker community. In this study, the Filipino concept of *Bayanihan*, a communal unity was noted as an important driver for implementing OSH. Other traditional practices could also be fruitfully investigated. For example, *Harambee* is a popular tradition in East Africa that also could be used to explain community work and the practices of the maker community.

6. Conclusion

There has been an unprecedented growth in activity from the maker community in response to COVID-19. This paper is an attempt at sensemaking to help build a shared understanding of community-driven OSH responses to COVID-19. We analyse six case studies using OSH to tackle the COVID-19 pandemic. In doing so, we document the contribution of OSH in a crisis, and we also investigate critical factors that influence the development of OSH from idea to implementation. The critical factors identified in this study are not intended to be fully exhaustive, however act as an early lodestar for guiding OSH in a crisis.

This study makes clear that implementing OSH in a crisis requires support from beyond the maker community. As well as building legitimacy and community management, the presence of enabling ecosystem conditions is needed to support OSH. In this study we draw attention to the novel and synergetic collaborations that are emerging between the maker community and other actors such as research institutions, non-governmental organisations and incumbent manufacturers. We suggest that further

work could help to better understand these heterogeneous collaborations by developing an in-depth and multi-perspective social network analysis.

Whilst this is a fast-moving field and the results presented in this paper are a single snapshot of the early response to COVID-19, we believe that this study has created a valuable foundation for studying the practices of the maker community, and understanding how OSH can be best used in a crisis. We intend to continue to document these case studies as the crisis response matures. Future studies might also consider a comparative study with OSH activities in previous crises. Research might also reflect on examples of failure to better understand the use of OSH in a crisis.

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Competing Interests

The authors have no competing interests to declare.

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