Using systems thinking to investigate the sustainability of digital fabrication projects in the humanitarian and development sector

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Abstract: Recently, designers have started using digital fabrication to create new solutions to meet global challenges. However, many technology projects in the humanitarian and development sector have been criticised for failing to deliver sustainable solutions. This study responds to these concerns by investigating the sustainability of digital fabrication projects in the humanitarian and development sector. A systems approach is used to synthesise knowledge from 14 digital fabrication projects in healthcare, education and water and sanitation. Causal loop diagrams are created to investigate the relationships between the drivers and barriers to sustainability. Several systems archetypes are also identified revealing potential leverage points for driving more sustainable solutions. The paper contextualises these findings by drawing on theories from participatory development and cosmopolitan localism. It concludes that digital fabrication presents an opportunity for more local and participatory design, however sustainability is being undermined by a tendency to seek short-term solutions.

Keywords: systems thinking; sustainability; digital fabrication; humanitarian; development.

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1 Introduction

The humanitarian and development sector are struggling to meet the rising demand for aid (Development Iniatives, 2018). Historically, technology has been viewed as a driver for social progress (Salam and Kidwai, 1991). Recently, the humanitarian and development sector have become interested in how technology can address global needs and help crisis-affected people (Corsini and Moultrie, 2020). A number of organisations have started using digital fabrication (3D printing, CNC milling and laser cutting) to produce essential items, such as prostheses, shelters, medical equipment and spare parts (Corsini et al., 2019). Collectively these projects can be referred to as digital fabrication for development (DF4D). Interest in DF4D has grown rapidly as it offers the potential to shorten the supply chain (Corsini et al., 2020; Tatham et al., 2018, 2015), support local development (Birtchnell and Hoyle, 2014) and to provide low-cost, customisable solutions (Saripalle et al., 2016).

Alongside this growing optimism, is the recognition that several technology projects have failed to deliver sustainable solutions to social problems (Pattnaik and Dhal, 2015). There is concern that recent DF4D projects may be one-off solutions that do not deliver long-term impacts (Corsini et al., 2019; Corsini and Moultrie, 2019). Within the aid sector, sustainability has often been used to refer to a project or an organisation's ability to sustain itself: "measuring whether an activity or impact is likely to continue after donor funding has been withdrawn" (ALNAP, 2007 in Haavisto and Kovács, 2014); "being able to survive so that it can continue to service its constituency" (Weerawardena et al., 2010). More broadly, sustainability is commonly defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987).

A previous study by the authors, based on literature, found several positive and negative factors that may affect the sustainability of digital fabrication projects (Corsini et al., 2019). There is an urgent need to gather empirical data to validate these factors and to examine their relationships. The following research responds to this gap in knowledge to investigate the sustainability of digital fabrication projects in reality. We use interview data as part of a systems thinking approach, to examine the cause and effect of different system elements (Meadows, 2008; Sterman, 2000). This approach synthesises fragmented knowledge from a range of projects. It provides necessary insights to avoid the pitfalls of previous technology projects, which have failed to deliver sustainable impact.

Our paper is structured in the following way. First, we describe the systems approach used to investigate sustainability of DF4D projects. Second, we describe the results of this study, revealing several causal loop diagrams that show common patterns of behaviour. We show that several reinforcing loops are enabling organisations to deliver impact, as well as observing that the tendency to short-term fixes is limiting impact. More broadly, our findings highlight that digital fabrication is driving increasingly local solutions, in which people, materials, tools and production are shifting from international to local networks. Finally, we draw on theories of participatory development and cosmopolitan localism to argue that digital fabrication therefore has a role in advancing sustainable development. This study makes important contributions to theory and practice by revealing how digital fabrication can promote more local, sustainable solutions.

2 Method and systems approach

Systems thinking helps to map the current reality in order to solve a particular problem [Sterman, (2000), p.79]. The following study investigates the sustainability of DF4D projects. In contrast to reductionist approaches, systems thinking takes a holistic view in which “the whole is more than the sum of its parts”. It is also concerned with cause and effect thinking, recognising that system elements are interdependent [Checkland, (1999), p.213].

To define the causal structure of the system, it is necessary to define a system’s elements and identify the causal links between these elements [Sterman, (2000), p.137]. By creating causal loop diagrams, it is possible to identify common patterns of behaviour and to identify leverage points for change [Sterman, (2000), p.137]. Table 2 provides an overview of the approach used in this study.

2.1 Data collection

To build up an understanding of DF4D projects, it was decided to conducted interviews with practitioners. Semi-structured interviews are considered to be an effective method for formulating systems models [Sterman, (2000), p.157]. Initially, projects were identified using online searches, word of mouth and attending conferences in the field. In an effort to capture the breath of DF4D projects, projects related to health care, water and sanitation and education were included in this search. A wide geographical area was examined, to identify DF4D projects in various low-resource settings (low income or lower-middle income countries).

Initial contact was made with organisations working on DF4D projects. Where possible, interviews with several employees were conducted to gather multiple perspectives on the same reality. This is an important way of building a shared reality, as people only have a local understanding of the system [Sterman, (2000), p.157]. In total, interviews were conducted with 27 designers, engineers and project managers. The interviewees represented 21 organisations, working on 14 DF4D projects. In some cases, follow-up interviews were conducted to gather data from ongoing projects. Table 1 shows the interviewee details.

Table 1 Overview of interviewee details

#	*Organisations*	*Example product case studies*	*Tech.*	*Location of manufacture*	*Project dates*	*Interviewees*
1	3D4MD, Médecins San Frontières (MSF)	Medical items and spares	3DP	East Africa	2018 (ended)	CEO and designer, 3D4MD (01-01) Project manager, MSF (01-02)
2	3D Life Prints	Arm prosthesis	3DP	East Africa	2013–present	CEO, 3D Life Prints (02-01)
3	AB3D	Medical shoe, surgical model	3DP	Kenya	2012–2014	CEO and engineer, AB3D (03-01) Designer, AB3D (03-02)
4	De Montfort, MNIT Jaipur, AHA 3D	Arm prosthesis	3DP	India	2017–present	Project investigator, De Montfort (04-01) Project investigator, MNIT (04-02) CEO, AHA 3D (04-03)
5	Glia	Tourniquets, stethoscope	3DP	Gaza	2017–present	CEO, Glia (05-01)
6	FabLab/MakerSpace Nairobi	Suction pump machine	3DP, CNC	Kenya	2013–present	Project manager, FabLab/MakerSpace Nairobi (06-01)
7	Field Ready	Medical items, spares, water pipe connectors	3DP, laser cutting	Nepal	2015–present	Innovation Lead, Field Ready (07-01) Program manager, Field Ready (07-02) Program manager, Field Ready (07-03) Designer, Field Ready (07-04) Monitoring and Evaluation, Field Ready (07-05)
8	Indian Institute of Technology-Bombay (IIT-B), BMVSS Jaipur	Leg prosthesis	3DP, CNC	India	2015–present	Project investigator and engineer, IIT-B (08-01) CEO, BMVSS Jaipur (08-02)
9	Médecins San Frontières (MSF)	Arm prosthesis	3DP	Jordan	2016–present	Project manager and engineer, MSF (09-01)
10	Not impossible	Arm prosthesis	3DP	South Sudan	2014–2016 (ended)	Project manager, not impossible (10-01) Engineer, not impossible (10-02)
11	Oxfam	Hand washing device	3DP	Lebanon	2015 (ended)	Project manager and engineer, Oxfam (11-01)
12	Refugee Open Ware	Arm prosthesis	3DP	Jordan	2016 (ended)	CEO, Refugee Open Ware (12-01)
13	Victoria Hand Project	Arm prosthesis	3DP	Nepal, Cambodia	2013–present	COO, Victoria Hand Project (13-01)
14	Waterscope, STIClab, Digital Blacksmiths, TechforTrade	Microscope	3DP	Kenya, Tanzania	2014–present	CEO and engineer, Waterscope (14-01) CEO and engineer, STIClab (14-02) CEO, TechforTrade (14-03) Engineer, Digital Blacksmiths (14-04)

Table 2 Overview of the stages of the research study

	Stage		*Approach*
1	Data collection on sustainability of DF4D* projects	1	Semi-structured interviews with designers, engineers and project managers
2	Identification of system elements	2	Code interview transcripts in MAXQDA, using positive and negative factors for sustainability identified in Corsini et al. (2019)
3	Exploration of causal links between system elements	3	Use MAXQDA maps to identify the relationships between factors
4	Creation of causal loop diagrams	4	Use thematic analysis to create maps in VensimPLE, crosschecking maps with interview data
5	Identification of leverage points to influence the sustainability of DF4D* projects	5	Analyse maps to using systems archetypes to find common patterns of behaviour and leverage points

Note: *DF4D – digital fabrication for development.

Although key questions were identified in advance, the interviews were fluid and discursive in nature. Emphasis was placed on gathering important information instead of asking a rigid checklist of questions (Fylan, 2005). First, organisations were asked to describe the project, including the digitally fabricated product they were developing or had developed. Second, they were asked about the aims and actual impacts of the project. Third, interviewees were asked to reflect on the barriers and enablers that influenced their outcomes, when working on DF4D projects. These factors are considered as potential positive and negative factors for the sustainability of digital fabrication projects. All the interviews were recorded with the participants' consent and were transcribed verbatim. The interview transcripts were imported into the software MAXQDA.

2.2 *Identification of system elements*

To begin with, the factors which may influence sustainability, identified in the previous study by Corsini et al. (2019) were used to create a coding hierarchy in MAXQDA. All the interview transcripts were coded in MAXQDA using these factors, and five codes were added: entrepreneurial talent; local manufacture of production tools; incentives for collaboration; attitudes and reluctance to change; and, local design. This led to the definition of 47 positive and negative factors that influence sustainability (see Appendix Table A1). In some cases, these codes were updated to reflect the actual language that was used by the interviewees. For example, the original code *participatory and bottom up design* was changed to *user participation*.

2.3 *Exploration of causal links*

To investigate the relationships between these factors, MAXQDA maps, an analysis tool in MAXQDA was used. MAXQDA maps generates diagrams to show the relationships between codes. Codes that were found to overlap at least twice in the interview transcripts are shown as linkages in Figure 1. The size of the circle reflects the number of times that code was mentioned by interviewees. This analysis has some limitations, as it overlooks cases when codes are adjacent but do not overlap. It also assumes that frequency is an indicator of importance, which may misrepresent the importance of factors. Regardless, it provides a useful starting point for investigating the key factors that influence sustainability and the relationships between them. The map provides evidence that causal links are directly supported by interviewee data.

2.4 Creation of causal loop diagrams

A causal loop diagram is useful for communicating important feedback that are responsible for a particular problem [Sternam, (2000), p.137]. In this case, we investigate the problem that some DF4D projects are not sustainable. Rather than mapping the entire system, each diagram corresponds to an important part of the story being told [Sterman, (2000), p.155]. In this analysis, we present three main causal loop diagrams. These are related to:

1 people

2 materials and tools

3 production.

These themes emerged after reflecting on the key elements in the design process and some of the important connections in Figure 1.

Figure 1 Map to show relationships between codes in interview data (see online version for colours)

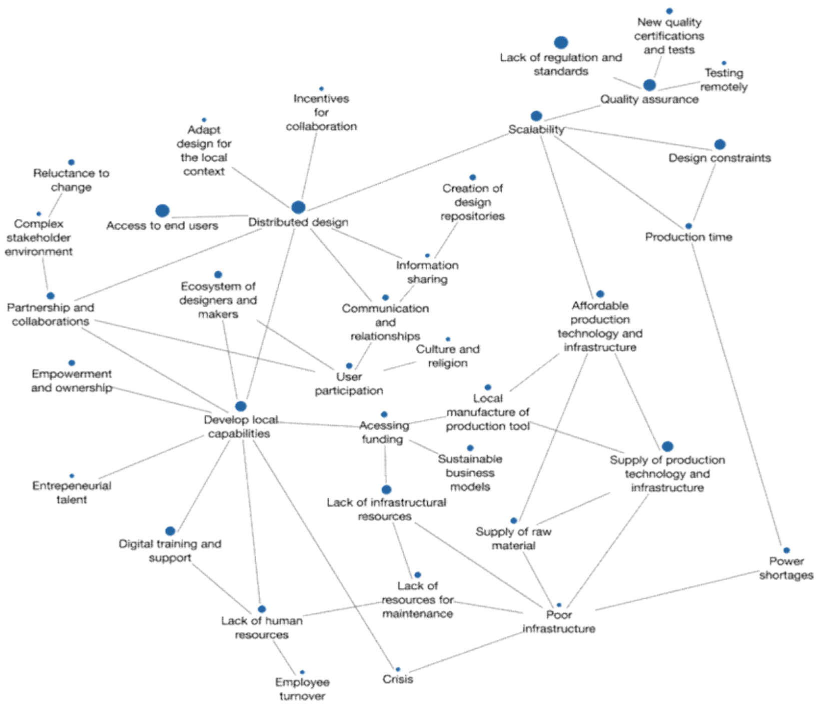


Table 3 Types of effects in causal loop diagrams

Types of effects	*Description*
Positive	A positive (+) arrow means that an increase in one variable causes an increase in another variable.
Negative	A negative (–) arrow means that an increase in the one variable causes a decrease in another variable.
Reinforcing loop	A reinforcing loop is when an action continuously reinforces a condition leading to spiralling growth or decline.
Balancing loop	A balancing loop is when a condition drives a corrective action that adjusts the original conditions. This leads to balancing, constraining or self-regulating processes.
Time delay	In some cases there is a time delay between a change in one variable causing a change in another variable. This is shown by two dashes on a link - ||

The causal loop diagrams were developed through an iterative process of comparing Figure 1 with the interview data, drawing on all experiences and knowledge to map the system [Sterman, (2000), p.158]. The diagrams are intended to represent general patterns found across the projects interviewed, not to represent a single project. In some cases, links not shown in Figure 1 were added, based on additional sources of data found in reports and articles about the DF4D projects. Some other links that represented obvious relationships that were not mentioned in the interviews were also included. The causal loop diagrams (see Figures 2–4) were created using VensimPLE software.

2.5 Identification of leverage points

Common patterns of behaviour found within systems have been identified as systems archetypes (Braun, 2002; Meadows, 2008). By comparing our causal loop diagrams with these well-known systems archetypes, it is possible to identify "recognisable story lines or plots that recur across a wide variety of social issues" [Stroh, (2015), p.68]. This analysis helps to develop a preliminary understanding of behaviour that influences sustainability and to suggest leverage points for driving change.

Table 4 Systems archetypes and attitudes

Systems archetypes	*Attitudes*
Limits to growth	"We can invest later on"
Shifting the burden	"We need a solution now, it's too difficult to address the fundamental solution"
Fixes that backfire	"Something is better than nothing"
Virtuous cycle	"The more we do this, the more impact we will have"
Balancing actions	"We can fix this problem"

3 Results

3.1 People

The first causal loop diagram (see Figure 2) focuses on *people*, referring to both human capital, i.e., the knowledge, information, ideas and skills of people (Becker, 1993) and social capital, i.e., networks with shared norms, values and understandings that facilitate cooperation (Healy and Côté, 2001).

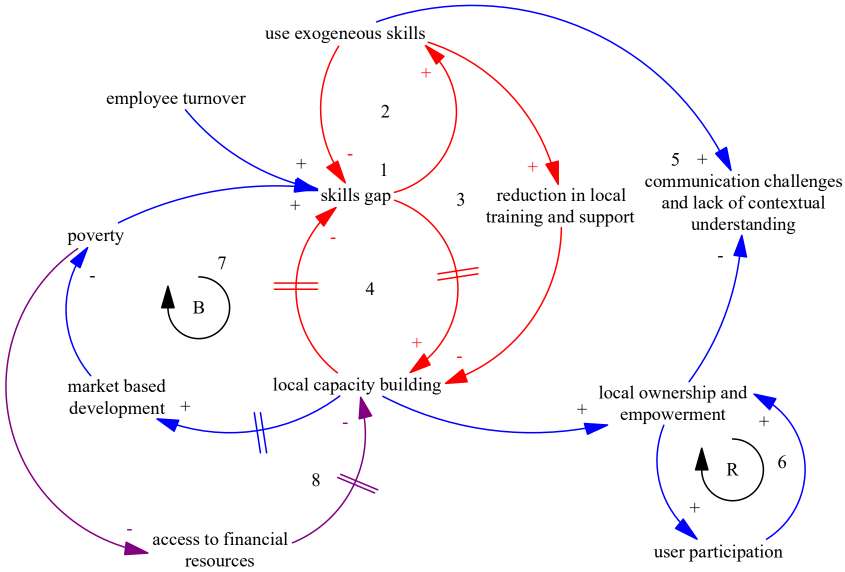
In many humanitarian and development contexts, there is a skills gap (see Figure 2, label 1). This is partly a result of employee turnover and the brain drain, as well as poverty, which undermines local education and resources for development.

> "I mean you do get the young guns that are smart, but the education system itself is terrible." (02-01)

> "The challenge was access to labour, access to affordable high skilled labour." (03-01)

> "It's been very detrimental within our society because the smartest, the brightest, these are the people who are targeted first... They're also the first people to leave when the opportunity arises. So between getting killed or leaving because you might get killed, very little of the talent remains." (05-01)

Figure 2 Causal loop diagram related to people (human capital and social capital) (see online version for colours)



This is a particular challenge for digital fabrication projects, as the technologies are relatively new and software mostly closed, increasing the barrier to entry for people low-income countries.

> "Not many people have used a 3D printer or the software that we use... It's quite a learning curve." (13-01)

Faced with a lack of local skills, some organisations rely on importing exogenous skills in order to reduce the skills gap (Figure 2, loop 2). This meets the immediate demand for skills, however means that there is a natural reduction in local training and support, which therefore reduces local capacity building (Figure 2, loop 3). Local capacity building takes time and its effect on reducing the skills gap may take several years (Figure 2, loop 4).

> "If you want to get there [achieve sustainable impact] you've got to start now because you need to start training people. It's going to take 5-10 years. The technologies are getting better and better, but the training is not, the skill sets aren't there. You need to completely overhaul the education system." (12-01)

However our findings reveal that local capacity building is a more fundamental solution that avoids some of the unintended consequences of relying on exogenous skills. For example, relying of exogenous skills can often lead to communication and cultural challenges (Figure 2, loop 5). A lack of understanding about the local context can result in inappropriate products being supplied. In contrast, local capacity building increases local ownership, which increases contextual understanding.

> "These guys know how it all works and how to deal with people here. To be honest I couldn't imagine working in any other way." (11-01)

Local ownerships and empowerment supports greater user participation, which in turn results in greater project ownership (Figure 2, loop 6). This reinforcing loop is an example of a *virtuous growth* that increases impact. Importantly, our findings suggest that organisations can create conditions to help facilitate participation by local communities, however cannot guarantee that active participation will necessarily occur.

> "You can support it as an outsider by providing the right infrastructure. But providing the right infrastructure won't make it happen and won't solve every problem that you think it might." (07-03)

Over time local capacity building offers the potential for job creation and market based development (Figure 2, loop 7). Local entrepreneurs can use digital fabrication to create products for commercial markets. This in turn reduces poverty and the skill gap, providing a *balancing action*.

> "We train them on using this technology… then they can get employment using this 3D printing." (04-02)

> "So I think if we have more makers using these tools, we have more people using 3D design skills, we'll start seeing new products and new devices come into the market." (10-02)

> "There are some economic benefits in terms of people making livelihoods, even though selling digital design or through accessing digital design and turning it into sellable products." (07-03)

However, it should be noted that local capacity building fundamentally relies on access to resources (Figure 2, loop 8).

> "It's about empowering and proving agency to affected communities, providing them with affected communities to develop the solutions to their own problems. So they need the tools, the training, the raw materials, you need international experts to chime in on things when people get stuck." (12-01)

> "When you think about scaling up and building capacity after that crisis, you want to start a local business. You want to empower that community to be able to start making things after you're gone." (01-01)

Almost all the interviewees emphasised the challenge of accessing funding. Our results showed that this leads to an increasing inability to address poverty (see Figure 2, loop 8). In the loop highlighted in purple, it can be seen that poverty reduces access to financial resources, which reduces local capacity building, which in turn fails to reduce poverty. In this case, financial support from the aid sector may provide relief. However, many organisations were critical of the aid sector's provision of short-term funding, instead of supporting sustainable growth.

> "They are far too reliant on what I call toxic money, you know they get their 100 grand grants and travel and they don't really think what's going to happen next year, they are just living year to year." (02-01)

> "It's a very fickle supply of cash if you count on the charity of the first world." (05-01)

Organisations should consider how they can minimise short-term fixes, in favour of more systemic solutions. Overall, the loops highlighted in red in Figure 2 reveal the problematic behaviour of *shifting the burden*. Rather than addressing the root cause of the problem (the lack of local skills), our findings show there is a tendency towards short-term fixes (importing exogenous skills). Although this makes sense in the short-term and may be necessary for delivering urgent aid, it undermines efforts in the long-term. More broadly, we underline the need for more sustainable support from the aid sector.

3.2 Materials and tools

The next causal loop diagram is related to the *materials and tools* used in production (e.g., 3D printers, filament, etc.).

Facing a growing number of crises, organisations are turning to digital fabrication for solutions (see Figure 3, link 1). This increases the demand for digital fabrication tools and materials, which have to be imported as they are not locally available (see Figure 3, loop 2). There are significant challenges importing digital fabrication tools and materials as infrastructure is often poor or disrupted and import taxes are expensive.

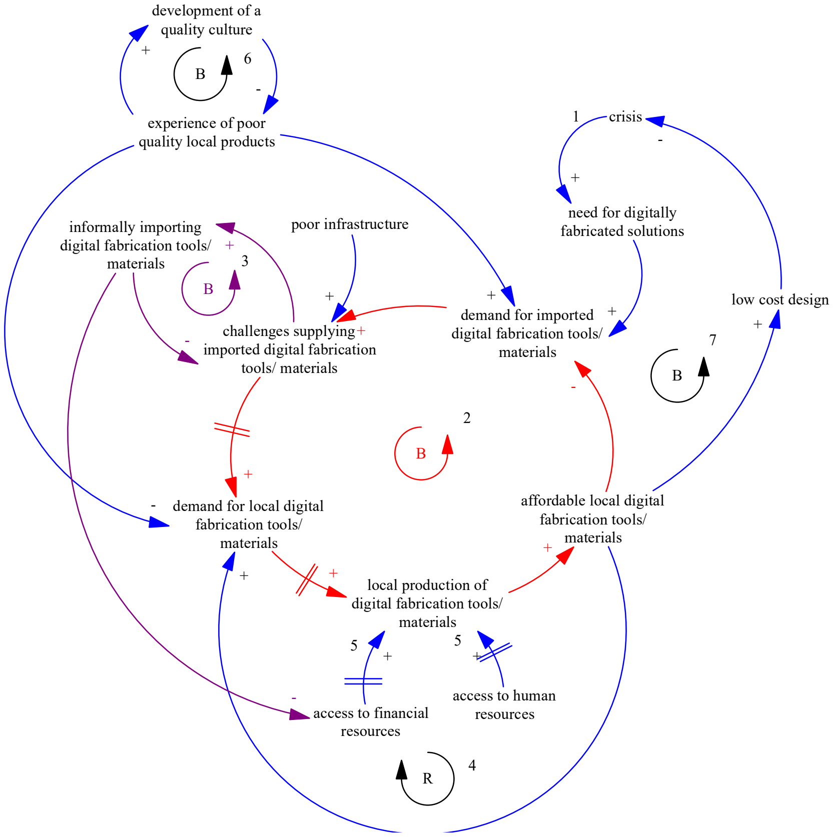
> "You're paying $45, $50, $60 for a kilo of filaments, and they have to be imported, and then there's duties to be paid, and again…it was kind of crazy that they were so expensive" (14-03)

> "Customs are just impossible, sometimes it's just impossible to even import stuff. So as much as you try and digitise the supply chain, you still need to import stuff, 3D printers or filament, and that tends to be next impossible in places like Jordan and turkey… 3D printers were banned at one point in Jordan." (12-01)

Some organisations relied on volunteers to informally transport tools and materials in their luggage to avoid challenges at customs. Our findings suggest that this activity is another example of *shifting the burden* (Figure 3, loop 3). Although it resolves the immediate problem, it diverts financial resources that could be invested into the local production of tools and materials, and it fails to provide a sustainable solution.

> "We got past it because we're small and informal, and you can hide a 3D printer in your luggage and no one's going to pull you up at customs." (07-03)

Figure 3 Causal loop diagram related to materials and tools (see online version for colours)



Seeking alternative solutions, demand for the local production tools and materials emerges. Once this demand reaches a critical level, there is enough incentive for local manufacturers to begin producing digital fabrication tools and materials. As demand increases, economies of scale mean that tools and material become more affordable. This further increases the demand for local digital fabrication tools, resulting in reinforcing loop of *virtuous growth* (Figure 3, loop 4).

> "So at some point we had to build our own machines – the CNC, 3D printers, even some other small tools that will facilitate us to do some other works…

> [having] our own tools will help us to be more sustainable… the cost is lower." (14-02)

The shift to local production thus reduces challenges supplying digital fabrication tools, providing a key *balancing action*. Furthermore, locally produced tools are believed to be more suited to the contextual needs of humanitarian and development settings. Using locally available resources also eliminates lengthy supply chains for importing spares and repairs.

> "Within probably a couple of months, in nearly every location, the printers that we donated were broken… the reasons were many and varied… irregular power supplies, fluctuations in voltage, causing machines to blow, high humidity, dusty environments. And then getting spare parts to actually repair the machines, in almost every case, required somebody to try and contact MakerBot in Brooklyn and then, unless their parts are fitted by a MakerBot registered engineer, you invalidate everything." (14-03)

Ultimately, the shift to local production relies on access to funding and human resources, which we identify as *limits to growth* (Figure 3, links 5). Moreover, the creation of this local production industry takes time, which may be an obstacle for organisations seeking immediate results.

> "The whole context is so much more challenging to sustain the project. It requires a lot more investment." (10-01)

In general, the interviewees suggest that there is a reluctance towards local production, because of negative perceptions about quality. We recommend that the development of a quality culture (Figure 3, loop 6) presents a long-term approach to improving the quality of local products. This *balancing action* can increase demand for local materials and tools, and reduce demand for imported goods. Finally, the increased affordability of materials and tools naturally improves the provision of low cost designs that can address crises (Figure 3, loop 7). This loop reveals another *balancing action* that mitigates crisis.

3.3 Production

The final causal loop diagram focuses on new modes of *production*, i.e., the design and manufacture of humanitarian and development items.

In response to crises, the humanitarian and development sector traditionally import products (see Figure 4, link 1). This leads to supply chain challenges, as infrastructure is often poor or disrupted. These experiences increase the demand for locally manufactured items. The diagram shows that local manufacture is facilitated by an ecosystem of designers and makers. This ecosystem fosters information sharing and greater partnership and collaboration, which in turn creates a more effective ecosystem of designers and makers (see Figure 4, loop 2). Ultimately, this highlights the *virtuous cycle* of collaboration that results in an ecosystem of designers and makers.

> "We've gotten the information out there by institutionalising all of it, by making partnerships with universities and colleges, and by trying to give as many people the opportunity to work with us as possible." (05-01)

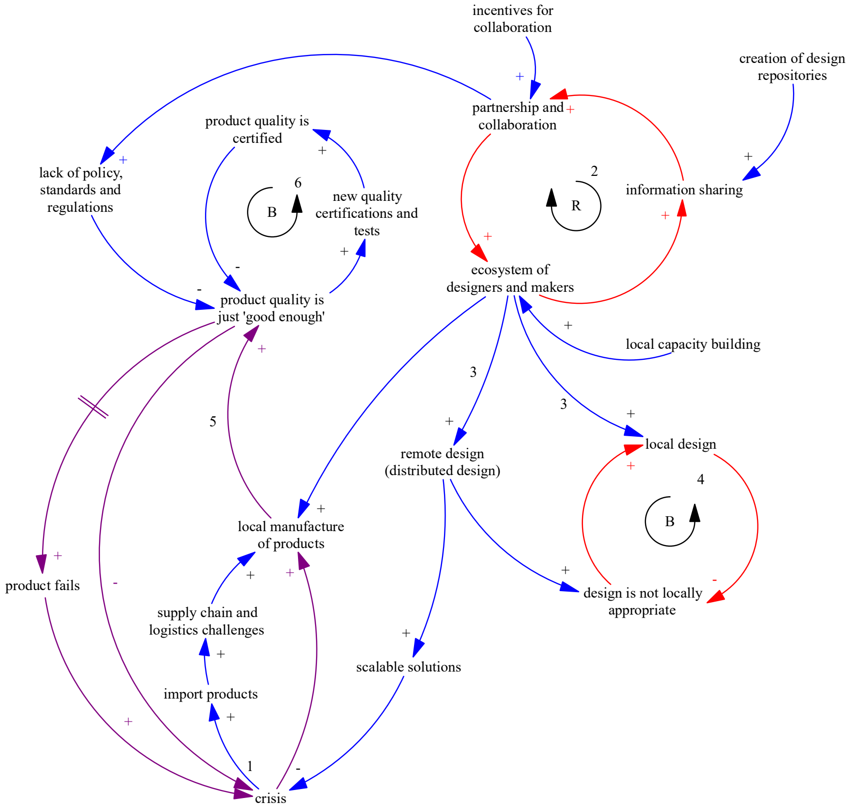
> "The 3D printing community in India… have started coming together as a consortium… we are able to help each other. We all know each other's problems and a lot of work is in front of us. Instead of competition right now there is synergy and comradery." (04-03)

To support information sharing and collaboration within the ecosystem, appropriate incentives for collaboration are needed. Individual actors need to understand how they can engage with the ecosystem, to convert its potential into tangible results.

> "If I develop a great product that can be digitally fabricated that I think would be a benefit to many people in a wide number of markets and a wide number of communities, how do I benefit from sharing my design? Can I benefit from sharing my design?" (14-03)

> "The Nairobi ecosystem has really helped us… I think we are in the right place at the right time… There's a lot happening, a lot of people excited about tech coming out of Nairobi… but the challenge is still navigating through that ecosystem." (06-01)

Figure 4 Causal loop diagram highlighting production-related elements (see online version for colours)



The ecosystem supports the integration of local design and remote (distributed) design (see Figure 4, links 3). Our findings highlight that collaboration between local and global actors is needed to develop scalable and appropriate solutions for local problems. Remote or distributed design increases scalability, by leveraging global resources and reducing unnecessary replication of effort.

> "You've got to crowdsource it. It's the only answer… where you just don't have enough resources to go around … It's not just straight forward crowdsourcing, it's actually crowdsourcing with a purpose. You've got to give people certain design parameters and constraints, and have them understand the low resource context that people we'll be deploying these 3D printers to." (01-01)

Clearly, one of the motivations for using digital fabrication is the potential to share digital designs across geographically dispersed locations. However, this also increases the risk that designs will not be locally appropriate. Local design is therefore necessary to adjust these designs to ensure that they are suitable for local needs (see Figure 4, loop 4). This *balancing loop* challenges the belief that as long as designs can be shared openly, distributed design is sufficient. Rather than viewing distributed design as a plug-and-play solution, our findings suggest that it should be seen as a springboard for local design.

> "Of course, one thing that I strongly believe is that we have to get beyond the idea that if somebody's managed to make a thing and put it on Thingiverse, it is by definition a product. It's not, it's just a thing that's on Thingiverse. So to take the WaterScope design and adapt it, for the educational market and for us to get it into 11 schools in Nairobi, we had to do an enormous amount of work… because the WaterScope doesn't have a box, but obviously if you're going to put it into a school, it needs to have a box, it needs to be sturdy. It doesn't have any instructions for use that are written such that a pupil could follow them and a teacher could follow them." (14-03)

> "We're trying to use the power of digital manufacturing to say, "Okay, we've done this in one place. Now we can transfer it to a new place." Sometimes it works and sometimes it doesn't, because context can be really wildly different… every location might need a little tweak" (07-03)

Finally, we recognise the potential challenge of *fixes that backfire*. In some cases, we found that organisations were using solutions that were just 'good enough' (see Figure 4, loop 5). This was driven by the belief that "something is better than nothing".

> "People have said, 'Well, what do you expect? It is Africa almost as if 'well, it's good enough for us' sort of thing." (14-03)

> "I think quality and safety is perceived as something which big organisations do, or the European Union does, or a factory does. It's not something that a person does, and I think that can be a very big issue" (07-03)

However, we suggest that although these solutions can provide a potential quick fix to the crisis, they may cause worse outcomes in long-term and exacerbate the crisis. In fact, one interviewee provided a direct experience to demonstrate this potential risk.

> "I'm sitting there with two models of the tourniquet. One model I knew had problems, and one model didn't. One model we had discovered the problem and we had fixed it. I decided to deploy the model with the known defect because I thought something's better than nothing. Well, in my own hand while I was using this model it broke on me, almost killing the patient who I was trying to treat at the time. He was shot in the leg. He was bleeding like crazy. He was definitely dying. We put on the tourniquet, twist the tourniquet, the bleeding settles, success, and then the thing breaks… I could have killed this guy because I thought that something was better than nothing… In that case nothing would have been better because then we would have used improvised

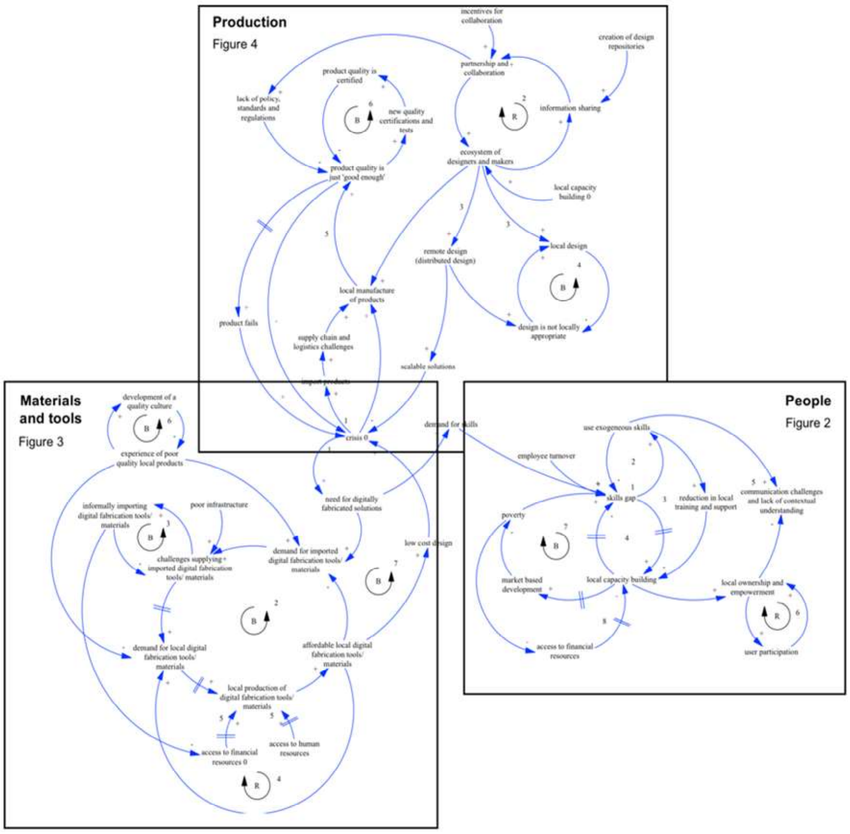
> techniques rather than thinking that we were going use this tourniquet, depend on it, lean on it, and then it breaks on us." (05-01)

It is essential that new quality certifications and tests are developed to overcome concerns with distributed design and production. Until this *balancing loop* is established, digital fabrication cannot deliver sustainable outcomes and will be limited to one off 'hacks'.

> "I think people who have been put off by the FDA process have been focused very much on the short term goals, which is 'okay, there's a problem here, this crisis, let's just fix it'… It all depends what your focus is and we've always taken the long term view… that you must do this if you want to scale up. You want ministries of health to buy into what you're doing, the first question they're going to ask you is, does this meet FDA or some sort of medical regulatory standard? If it doesn't, well then you're just always going to be limited to putting out fires and hot spots, but you will never scale up." (01-01)

> "Until some of the legal issues on liability around 3D printing and medical licensing is resolved, then I don't think we can actually pursue these things much further, in terms of actually distributing [items] to clinics and them using them." (07-02)

Figure 5 Integrated causal loop diagrams (see online version for colours)



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We emphasise that the creation of such regulation requires collaboration from multiple different actors, including government and regulatory bodies.

> "We need change at a policy level also… 3D printing domain has a huge scope of medical applications, but getting the certifications in place, and first of all, even knowing the policies [is a challenge]… we don't know who to approach… the red tape around it, we don't know how to get around that." (04-03)

Table 3 Summary of systems archetypes, attitudes and key actions

Systems archetypes	*Attitudes*	*Key actions*	*Reference (figure #)*
Virtuous cycles	"The more we do this, the more impact we will have"	Keep growth in check and be mindful of any unintended consequences or limits to growth	F2-6 F3-4 F4-2
Balancing processes	"We can fix this problem"	Monitor that balancing action has desired effect.	F2-7 F3-2, 6, 7 F4-4, 6
Limits to growth	"We can invest later on"	Identify limits and plan to allocate resources.	F2-8 F3-5
Shifting the burden	"We need a solution now, it's too difficult to address the fundamental solution"	Identify the addictive solution to the problem, and start addressing the fundamental solution no matter how difficult.	F2-2, 3, 4 F3-3
Fixes that backfire	"Something is better than nothing"	Recognise the unintended consequences of the quick fix, and take actions to solve the problem.	F4-5

4 Discussion

This paper has responded to concerns that DF4D projects lack long-term thinking and are struggling to deliver the impacts they desire (Corsini et al., 2019). We have adopted a systems approach to investigate the drivers and barriers of sustainability in this context. In doing so we have revealed three thematic models related to:

1 people

2 materials and tools

3 production.

These models have highlighted many positive behaviours that are expected to drive impact as well as highlighting problem-generating behaviours that are limiting sustainability. These findings reveal the potential of causal loop diagrams to make explicit the cause and effects within a system, and to encourage action through identifying blind spots. They also allow us to interrogate the sustainability question from a relative and temporal perspective (Sarriot et al., 2015).

In the causal loop diagrams, we have identified several virtuous cycles that are increasing impact. First, looking at the *people-based diagram* we predict that an increase in ownership and empowerment will reinforce user participation, thereby increasing the potential for ownership. Second, considering *materials and tools* we show that as the demand for local digital fabrication tools increases, they become increasingly more affordable and therefore desirable. Third, focusing on *production* we expect that greater partnership and collaboration will help to foster an ecosystem of designers and makers that encourages information sharing within an enabling ecosystem. In all of these models, the relationship between local and sustainable solutions is made clear. Our findings confirm that digital fabrication is increasing the *potential* for local solutions; however, this is not necessarily happening in all stages of the supply chain.

This study shows that the persistence of importing resources (including human resources, materials and tools) reveals a tendency to shift the burden. In the search for quick fixes, there is an apparent reluctance to address the underlying need to invest in local capabilities. The people-model (Figure 2) makes clear that this behaviour is problematic. It shows that importing skills undermines local capacity building and potentially results in the creation of less contextually appropriate products. Furthermore, the materials and tools-model (Figure 3) shows that formally or informally importing materials and tools (e.g., 3D printers and filament) disincentivises the creation of a local production industry, which could have led to wider socio-economic benefits (Birtchnell and Hoyle, 2014). As pointed out by the interviewees, local production of materials and tools is also expected to result in more low-cost, reliable, and easy to maintain and repair solutions. Our findings show that despite rhetoric that digital fabrication is driving more local solutions (Diez, 2018), imported resources are still being used as a quick fix.

There is an urgent need to distinguish between short-term small successes and quick fixes. As Stroh (2015, p.43) explains "quick fixes are solutions that produce short-run benefits, which are typically neutralised or eroded by longer run consequences of the same actions. Short-term small successes are improvements that are planned from the beginning with the long term in mind and are vital to encouraging persistence and maintaining momentum." This is a particular challenge in the humanitarian and development sector, in which interventions are either short-term or expected to end after a particular duration. Our findings highlight the problematic attitude: "something is better than nothing". The production-model (Figure 4) shows that using products that are perceived to be 'good enough' but do not meet rigorous quality standards, can exacerbate the original crisis if they fail. This system archetype – the fix that backfires – is an example of a quick fix being mistakenly taken as a short-term small success. We urge policy makers and government to take an active role in developing new standards and regulations. We also highlight the pressing need for new product quality certifications and tests. More broadly, we echo calls for a more coherent approach to humanitarian and development aid (OECD, 2017), to ensure that short-term plans are consistent with long-term goals.

On the whole, our findings suggest a new, more sustainable relationship between local and global production. The study underlines the potential for distributed manufacturing, i.e., local, connected and decentralised sites of design and manufacture, to leverage resources in different geographical locations. The fundamental difference between this approach and traditional approaches is that resources are not 'imported' but instead, designs are shared so that they can be locally adapted and implemented. We strongly contest the view that distributed manufacturing enables products to be instantly 'made anywhere' (Srai et al., 2016). Rather distributed manufacturing can be a catalyst for local design, which is necessary to adapt solutions for the local context. In addition, distributed manufacturing disrupts the traditional one-way flow of products from the

Global North to Global South in the aid sector (VanderSteen et al., 2009). Instead, designs can be locally driven and shared to create mutually beneficial outcomes that enrich global production.

These findings provide evidence that digital fabrication expands *cosmopolitan localism*, "a creative balance between being rooted in a given place and community and being open to global flows of ideas, information, people, things and money" (Manzini, 2013). This local and connected approach is highly relevant to the sustainability of digital fabrication projects, as it is believed to promote community resilience (Manzini, 2014; Manzini and Rizzo, 2011). Alongside this, our findings highlight the relationship between participation and sustainability. This aligns with calls for more participatory development (Nelson and Wright, 1999) and the increasing recognition of the agency of affected communities (Betts et al., 2015; Ekren, 2017).

Overall we recognise that many projects are in their relative infancy and can be viewed as experiments or *prototypes* (Hillgren et al., 2011). However, in order to realise long-term impacts, there is a need to transition from opportunistic to strategic approaches. The potential for digital fabrication to support more local and participatory solutions could advance sustainability. However, we have highlighted several barriers that need to be addressed first. In general, there is a need for more systemic thinking that avoids quick-fixes. Additional resources must also be allocated to local capacity building and local production of digital fabrication tools. Finally, concerns around quality require urgent attention.

5 Conclusions

In this study, we investigated the sustainability of digital fabrication for humanitarian/development (DF4D) projects. We adopted a systems thinking approach, conducting semi-structured interviews with 27 practitioners working on 14 unique DF4D projects. This research built on our previous work (Corsini et al., 2019), which identified factors that can positively and negatively impact the sustainability of DF4D projects. In this study, we developed three thematic causal loop diagrams related to:

1 people

2 materials and tools

3 production.

These causal loop diagrams provide linkages between different system elements, to show cause and effects. We revealed several systems archetypes, including: virtuous cycles, balancing processes, limits to growth, shifting the burden and fixes that backfire. Overall, we reflect a tendency in the humanitarian and development sector to seek short-term solutions. Our causal loop diagrams make explicit how these quick fixes and other behaviours are undermining the goal of sustainability. They also reveal leverage points for improving the current system.

The causal loop diagrams build a useful picture of the current reality of DF4D projects, however there are some limitations of this approach. First we recognise that these diagrams are only provisional representations of reality, which are "useful for guiding further study, but are not susceptible to proof" [Oreskes et al., (1994), p.644]. Second, we made efforts to capture as many interviewee perspectives as possible, however there remains the possibility that some views have been overlooked. Third, our causal loop diagrams have been created to represent a generic scenario and are not representations of any individual project case. There is the risk that in creating a generic model we have lost some details or misrepresented the importance of certain factors.

Our study builds on theories of participatory development and cosmopolitan localism to show that digital fabrication can promote more local, participatory and ultimately sustainable solutions. We also demonstrate the value of causal loop diagrams for analysing multiple projects. Practically, we identify several drivers and barriers that are influencing sustainability. This much-needed study provides valuable insights for organisations who are concerned about the sustainability of their DF4D projects.

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Appendix

Table A1 Negative and positive factors for sustainability in DF4D

Focus			*Negative factors*		*Positive factors*
Context	Environment and geography	1	Poor access to end users	1	Renewable power
		2	Power shortages	2	Recycled raw material
		3	Crisis		
		4	Poor infrastructure		
		5	Harsh environmental conditions		
	Resources	6	Lack of resources for maintenance	3	Combine digital fabrication with local production methods and materials
		7	Lack of infrastructural resources	4	Modular and reconfigurable designs
	Economic, political and legal	8	Attitudes and reluctance to change	5	Incentives for collaboration
		9	Financial constraints	6	Partnerships and collaboration
		10	Complex stakeholder environment	7	Sustainable business models
		11	Disrupted political environment		
		12	Lack of regulation and laws		
	Social	13	Lack of human resources	8	Training and support
		14	Poor contextual knowledge	9	Empowerment and ownership
		15	Communication and relationships	10	Entrepreneurial talent
		16	Employee turnover		
Technology	Design and manufacturing	17	Design constraints, e.g., size, material, tolerance, surface finish, strength, robustness	11	Affordable production tools
		18	Scalability	12	Desirable outcomes
		19	Production time	13	Local production tools
				14	Technological R&D
	Systems and infrastructure	20	Quality assurance	15	Creation of design repositories
		21	Supply of production technology and infrastructure	16	Ecosystem of designers and makers
		22	Supply of raw materials	17	Develop local capabilities incl. technology and infrastructure
		23	Poor information sharing	18	Testing remotely and in-field
				19	New certifications and tests
				20	Quality culture
	General approach			21	Open source design
				22	User participation
				23	Distributed design
				24	Local design

Source: Adapted from Corsini et al. (2019)