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The impact of 3D printing on the humanitarian supply chain

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ABSTRACT
Additive Manufacturing or 3 D printing is radically changing the way products are designed and manufactured. The humanitarian sector has started exploring how 3 D printing can help match supply with the global rise in humanitarian needs. However, there has been very little academic research in the field. This study aims to bridge this gap by reviewing twelve case studies of 3 D printed products to examine the effects of 3 D printing on the humanitarian supply chain. The findings reveal four supply chain archetypes, which demonstrate that 3 D printing is impacting the humanitarian supply chain with respects to networks, governance, processes and products. We compare the benefits and challenges of these archetypes to contest that 3 D printing will not necessarily simplify and shorten the supply chain. Instead, we suggest the need for a holistic supply chain approach that includes the local production of 3 D printers and filament, alongside local design and manufacture. This much-needed study provides the foundations for future academic research and offers relevant guidance for practitioners using 3 D printing in the humanitarian sector.

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3D printing; additive manufacturing; development; humanitarian; supply chain

Introduction

Additive manufacturing or 3 D printing (3DP) has received widespread acclaim as a disruptive technology that will revolutionise design and manufacturing (Hyman 2011; Garrett 2014). Since low-cost 'desktop' 3DP became widely available to the mass-market, interest in the technology has grown exponentially (Wohlers and Caffrey 2013; Shah et al. 2017). Specifically, its potential to create novel forms (Cheong et al. 2011; Ford and Despeisse 2016), enable mass-customisation (Gibson, Rosen, and Stucker 2015; Shukla, Todorov, and Kapletia 2018) and support low-volume, distributed production (Petrick and Simpson 2013; Rayna and Striukova 2016) has led to its reputation as a pioneering technology.

Recently, the humanitarian sector has become interested in how 3DP might help to address global needs. The rapidly growing demand for humanitarian aid is creating an urgent need for new solutions (Behl and Dutta 2019). In the media, there have been an increasing number of reports on humanitarian applications of 3DP, with projects in health care (Leach 2014; Davies 2018), water and sanitation (McBride 2014; Tess 2016) and architecture (Young 2017). Such applications are particularly relevant for the restoration and reconstruction stages of humanitarian responses (Cozzolino 2012). Despite the increasing number of these projects, academic research in the field is lacking, which makes it difficult to separate reality from some of the claims about 3DP found in the media (The Economist 2012, 2017). Furthermore, there is little guidance for practitioners using 3DP for humanitarian applications.

Severally studies suggest that that 3DP will have a significant impact on supply chains. 3DP is projected to shorten the supply chain (Shah et al. 2017), reduce complexity (Mohr and Khan 2015) and improve resource efficiency (Liu et al. 2014). Underlying this is the common belief that 3DP will enable more localised and direct forms of production (Wagner and Walton 2016; Ryan et al. 2017; Shukla, Todorov, and Kapletia 2018). If proven, these potential impacts of 3DP are highly relevant to the humanitarian sector, as it must respond quickly to unpredictable events under significant resource constraints (Costa, Campos, and Bandeira 2012).

There are similarities between traditional supply chains and humanitarian supply chains (HSCs), but also important differences (Oloruntoba and Gray 2006; Heaslip, Kovács, and Haavisto 2018). Unlike conventional supply chains, the HSC is notoriously unpredictable (Balcik and Beamon 2008; Kovács and Spens 2009), resource constrained (Balcik and Beamon 2008; Oloruntoba and Gray 2006) and subject to delays and sudden spikes in demand (Kovács and Spens 2007). Additionally, HSCs have vastly different aims to traditional supply chains (Costa, Campos, and Bandeira 2012). Therefore examining the impact of 3DP *specifically* on the HSC is important because of its unique context and characteristics.

Given the recent convergence of humanitarian and supply chain research (Behl and Dutta 2019), existing research on the impact of 3DP on HSCs is extremely sparse. A recent review of digital fabrication in the humanitarian and development sector suggests that 3DP can help to overcome supply chain challenges (Corsini, Aranda-Jan, and Moultrie 2019). Among few studies that specifically investigate the impact of

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3DP on humanitarian logistics, Tatham, Loy, and Peretti (2015), explore a pilot project to produce water pipe connectors. Importantly, they recognise that the location of a 3 D printer along the supply chain will have widespread supply chain implications with respects to logistics, postponement and training. Alongside later work in Tatham, Heaslip, and Spens (2018), the authors put forward a 'hub and spoke' supply chain model, where design and testing takes place in a central facility (the hub) and the product is locally manufactured in-field (the spoke). Clearly, this is just one possible approach and other supply chain models are still needed.

Other studies examine 3DP in the disaster context. Schoning and Heidemann (2016) and De la Torre, Espinosa, and Domínguez (2016) explore the role of 3DP for producing spare parts after disaster; Bassett, Carriveau, and Ting (2015) look at 3 D printed wind turbines for disaster relief and rural electrification; Chu et al. (2015) prototype 3 D printed robots and UAVs for disaster response; Gregory et al. (2016) investigate 3DP for producing disaster shelters; Wong (2015) and Savonen et al. (2018) describe the capabilities of a resilient 3 D printer for the disaster context; Dotz (2015), Saripalle, Bush, and Lundman (2016) and Ibrahim et al. (2015) present examples of 3 D printed health care supplies in resource constrained settings; and, Rodríguez-Espíndola and Beltagui (2018) identify that 3DP could be used to produce shelters, settlements and non-food items, in humanitarian crises.

Overall these studies suggest that there is significant potential for 3DP to respond to humanitarian needs, yet there is little evidence to show the exact nature of 3DP's impact on the HSC. In particular, there is a little understanding of how 3DP will change the structure, management, operations and capabilities of the HSC. The following study addresses this lack of knowledge examining how 3DP is impacting the HSC. The purpose of this study is not to compare the outcomes of 3 D printed items with their conventionally manufactured alternatives, but to explore how 3DP changes the HSC.

The paper is structured in the following way. First, we present data collection and analysis methods, describing the selection of twelve case studies of 3 D printed products that meet humanitarian needs. Second, we reveal four supply chain archetypes, which describe different ways in which 3DP is impacting the HSC, with respects to networks, governance, products and processes. Then we discuss the results, contrasting our findings with conventional wisdom that 3DP will reduce complexity and shorten the supply chain. Finally, we discuss the theoretical and practical implications of this study, indicating areas for future research.

Method

To review the impacts of 3DP on the HSC, we adopted an inductive method using holistic, multiple case studies (Yin 2018). Case study research offers detailed explanations of real-world phenomena (Yin and Davis 2007) and multiple case studies are generally considered to provide more robust insights (Herriott and Firestone 1983). This approach provides much-needed empirical data on 3DP and supply chains (Durach, Kurpjuweit, and Wagner 2017).

Data collection

This study examines the humanitarian needs that require HSCs as opposed to the disaster zone. This approach is consistent with the belief that HSC Management is related to both disaster relief and development aid (Kovács and Spens 2007; Tabaklar 2017).

Maximum variation sampling (Patton 2002) was adopted to purposely identify organisations that use 3DP to produce items that respond to natural and man-made disasters (e.g. conflict), and poverty. The sample focussed on product applications in low resource settings, namely low-income and lower-middle income countries (World Bank Group 2017). Over a period of twelve months, as many organisations as possible were identified using online searches, press articles, snowballing and personal networks. Organisations were contacted between July 2017 and July 2018, resulting in contact being made with eleven of them. This sample reflects some of the key initiatives in this relatively small but growing field.

Initial interviews were conducted with designers or project managers at the organisations to identify various 3 D printed products as suitable case studies. Secondary data sources were also reviewed, including documents, reports and press articles. Interviews were conducted via skype or in person, with each interview lasting between 60–90 min. All the interviews were recorded with the participants' consent and complemented with note-taking. Interviews were semi-structured, with three main parts. First, interviewees were invited to describe the (or a typical) 3 D printed product which the organisation had developed. Second, they were asked questions about the supply chain of the product, in order to elicit the key differences between the traditional supply chain (for an non-3D printed product). Third, they were asked to reflect on the impacts of 3DP on HSCs, explaining how 3DP helped to address supply chain challenges. They were also asked questions more broadly about the benefits and challenges of using 3DP in the humanitarian sector.

Where possible, additional interviews were carried out with other employees, including designers, managers and partner organisations. For on-going projects, follow-up interviews were also conducted to check progress over the twelve months of data collection. This helped to validate the data and improve its robustness through triangulation (Denzin 1978). As part of related research, in-field visits were also conducted in four of the cases (see Appendix Table 1 for case studies 6, 7, 9, 12). In these visits, the first author directly observed, shadowed and interviewed people which provided complementary insights for this research. In total, forty-one interviews were completed between July 2017 and September 2018. The key informants who provided the most relevant and useful data related to the HSC are listed in Appendix Table 1.

Table 1. Impact of 3 D printing on supply chain network, governance, process and product.

Archetype	1. Centralised production at a local manufacturing hub	2. Fixed production facility at implementing organisation	3. Mobile production facility at implementing organisation	4. Distributed production at local manufacturing hubs
Network	– Reduction in number of upstream tiers by eliminating need for warehousing. – Manufacturing at local hub in country. Finished products are transported to multiple implementing organisations. – Manufacturing is localised. Shift to importing materials and tools instead of finished goods. – Design is distributed (international).	– Reduction in number of upstream tiers, through disintermediation of international and local suppliers. – Manufacturing on-site at implementing organisation. Direct distribution of finished products to ends users. – Manufacturing is localised. Shift to importing materials and tools instead of finished goods. – Design is distributed (international).	– Reduction in number of upstream tiers, through disintermediation of international and local suppliers. – Mobile manufacturing facility travels to implementing organisation. Direct distribution of finished products to end users. – Manufacturing is localised. Shift to importing materials and tools instead of finished goods. – Design is localised (on-site at implementing organisation).	– Elimination of international upstream tiers and creation of new local upstream tiers. – Distributed manufacturing at multiple makerspaces/ local manufacturing hubs in country. – Finished products are transported to implementing organisations. – Production of 3D printers and filament is localised. – Design is localised and distributed (created at a local hub and shared with other local hubs).
Governance	– Collaborative relationships between design and manufacturing team. – Information sharing across supply chain facilitated by digital communications.	– Collaborative relationships between design and manufacturing teams. – Information sharing upstream between manufacturing and material/tool (3D printer and filament) producers. – Information sharing between end users and manufacturing team, facilitated by IT solutions.	– Direct design and manufacturing. – Improved information sharing downstream. – Reduced number of actors in supply chain.	– Distributed supply chain. – Collaborative relationships between design and manufacturing teams. – Information sharing across supply chain facilitated by digital communications.
Process	– Collaborative – Increased circularity	– Collaborative – User-driven – Reduction in product complexity (fewer parts)	– User-driven – Increased circularity	– Participatory – Resilient – Contextual (using endogenous knowledge)
Product	– On demand – Customisation	– Mass customisation	– Customisation – One-off items	– Low cost – Product complexity – Contextually appropriate
Example products	– Spare or repair parts	– Prosthetics – Spare parts	– Spare or repair parts	– Prosthetics – Complex medical equipment

Data analysis

To start with, the case studies were analysed in terms of type of product and humanitarian scenario (see Appendix Table 1). Next, using Lambert, Cooper, and Pagh (1998) as guidance for illustrating supply chains, supply chain maps were produced for each of the case studies. Two case studies describe the same product, a 3 D printed prosthetic, which was implemented in Nepal and Cambodia. As the supply chain for the prosthetic was significantly different in the two locations, they were mapped as separate cases.

The new supply chains were analysed with respect to the following elements: (1) *network* e.g. location and geographic dispersion, upstream and downstream tiers and supply chain linkages (Srai and Gregory 2008; Chandra and Grabis 2016); (2) *governance* e.g. relationships, information sharing, ownership (Lin and Shaw 1998; Srai 2007); (3) *process* e.g. value and non-value adding activities and process steps (Srai and Gregory 2008); and, (4) *product* e.g. variety, complexity, modularity, value structure (cost of products etc.) (Srai 2007; Chandra and Grabis 2016).

After several rounds of discussion between the authors, four groups of similar supply chain patterns were identified, resulting in the creation of four *supply chain archetypes*. Table 1 summarises the archetypes in terms of network, governance, process and product. The supply chain maps for these archetypes (Figures 1–4) focus on highlighting common patterns and important new relationships within each archetype. Interviewees were consulted to verify that these archetypes accurately reflected their organisation's supply chain in generic terms.

Results

We will introduce four archetypes to reveal the different ways that 3DP is impacting the supply chain with respects to networks, governance, processes and products. We will conclude each archetype by summarising the key benefits and challenges associated with that particular supply chain configuration (see Tables 2–6).

Centralised production at a local manufacturing hub

The first archetype (see Figure 1) describes a scenario in which production takes place at a local manufacturing hub.

For example, a production facility might be established at an in-country NGO headquarters so that items can be 3 D printed and then distributed to implementing organisations. This approach is believed to overcome the supply chain

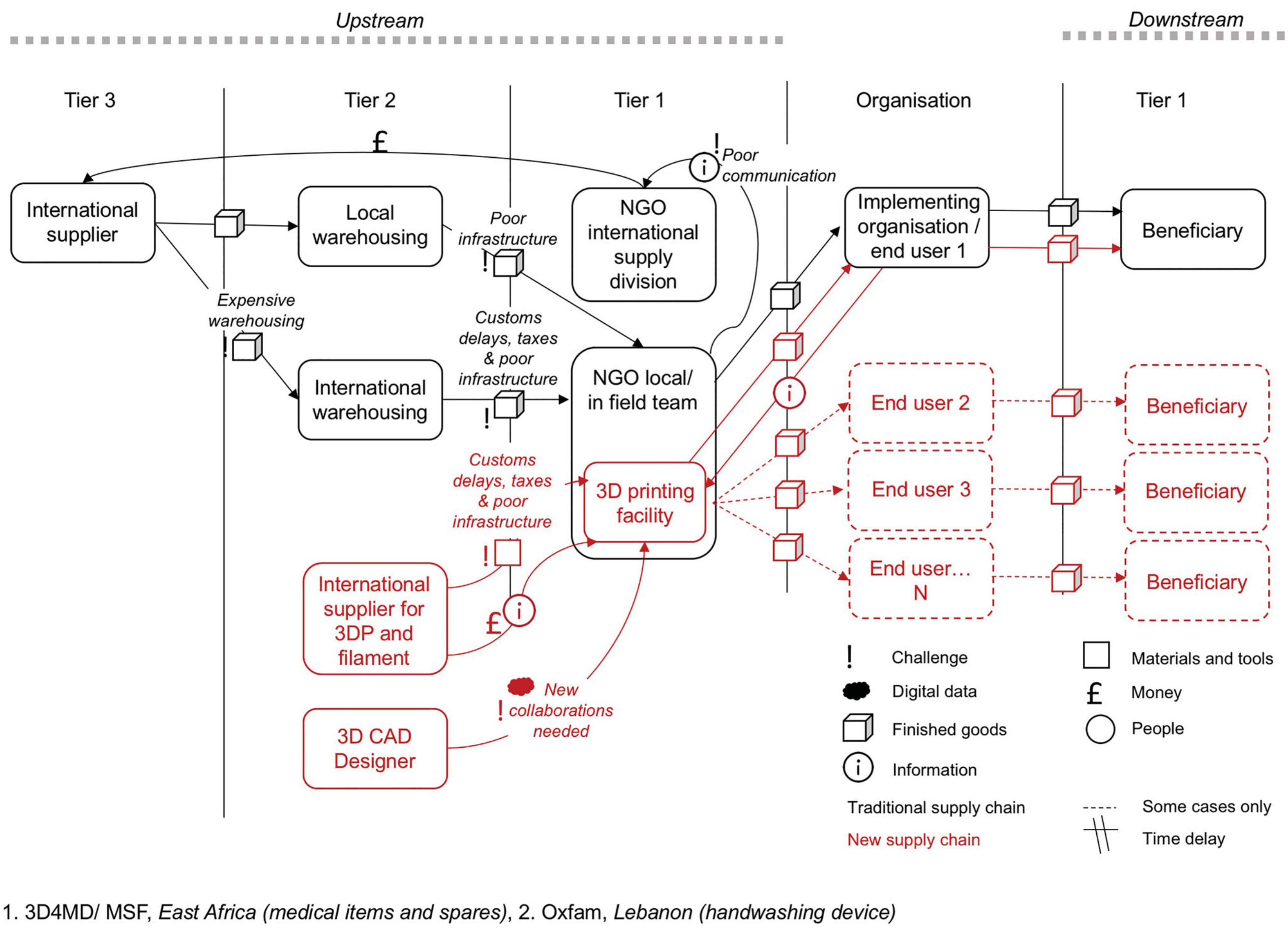


Figure 1. Centralised production at a local manufacturing hub.

challenges of importing finished products, and is suitable for producing simple items that can be easily manufactured locally. It reduces the need for warehousing, which is a common practice among humanitarian NGOs.

> So if you are ordering something internationally, if it's been procured, rather than just in stock somewhere, then it will take months… So the concept is quite simply that, for things that are not particularly complex, we could potentially make them locally. (CS1-02)

In this model, designers are typically located in the Global North and share digital designs with the manufacturing facility in the Global South. Distributed design is seen as necessary way to meet the volume of demand.

> Sending a bunch of us out to the field to every site to CAD stuff locally, that's just not scalable… You've got to outsource it, and you've got to crowd source it where you just don't have enough resources to go around. (CS1-01)

Information sharing across the supply chain is facilitated by digital communications, in open or closed networks. This supply chain necessitates collaborative relationships between geographically dispersed design and manufacturing teams. Whilst distributed design creates new possibilities for scaling-up responses, in some cases the design team's lack of familiarity with the local context may limit the suitability of designs.

> Crowdsourcing didn't end up with many ideas that were very workable in the end. (CS2-01)

3DP can be used to support greater customisation and on-demand production. It also increases circularity in the supply chain, as the production of spares and repairs eliminates the need to procure replacements for entire units.

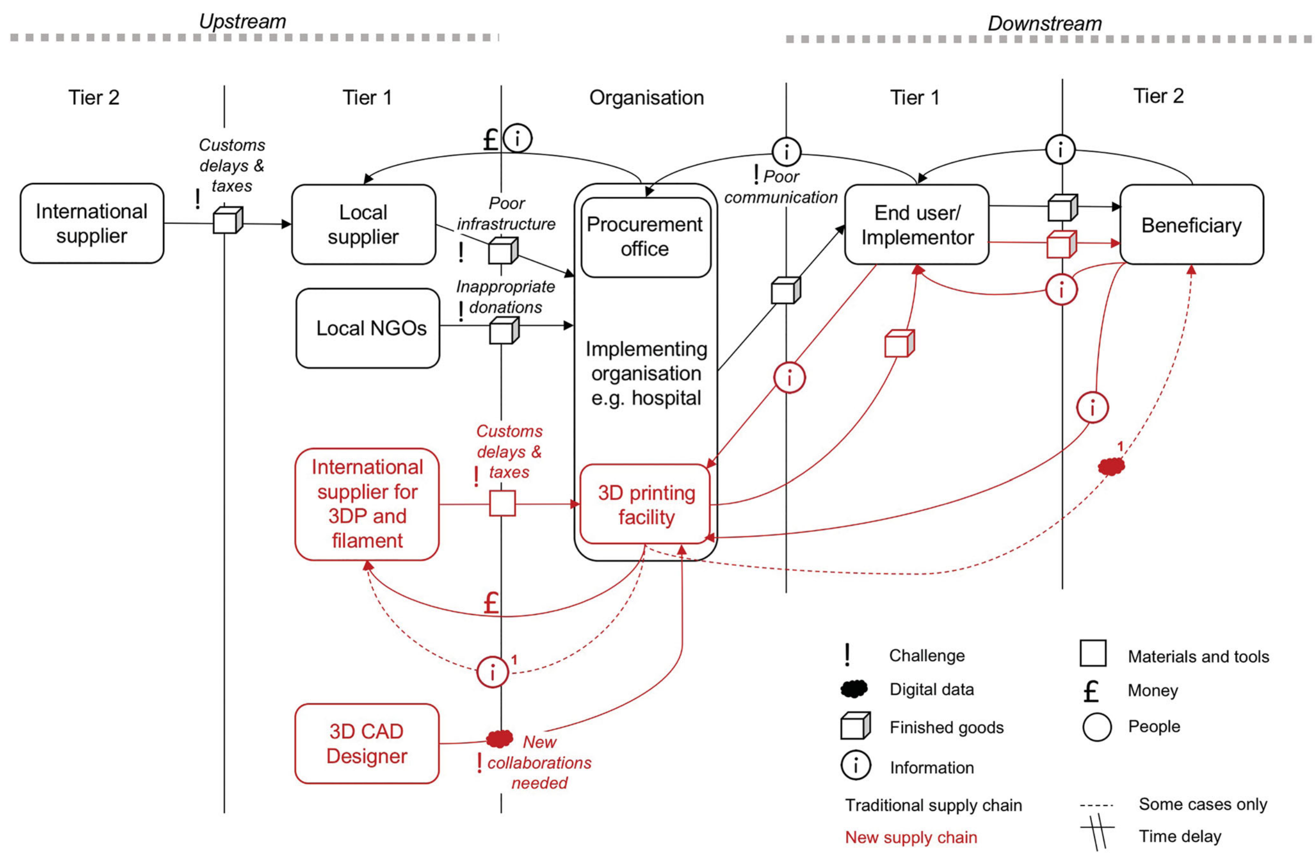
> We're working on a project where we can basically create a digital hack to make a broken piece of medical equipment functional again. (CS1-01)

The case studies identified that security and available infrastructure were key factors for selecting the manufacturing location. Establishing a 3DP facility at an existing NGO facility with available infrastructure, was considered preferable to setting one up further downstream, even if this would reduce the challenges of last-mile distribution of finished goods.

Whilst this approach eliminates the need to import finished goods, it should be noted that the supply of 3 D printers, filament and spare parts still requires an international supply chain. Furthermore, 3DP is limited to a small range of products. So rather than totally replacing the traditional supply chain, 3DP is expected to introduce an additional supply chain for humanitarian organisations.

> But for water and sanitation, you often need big bits of kits which you often cannot print. (CS2-01)

Overall, the case studies recognised that the recruitment of a local, endogenous manufacturing team was necessary to



3. 3D Life Prints, *East Africa (arm prosthetic)*, 4. Not Impossible, *South Sudan (arm prosthetic)*, 5. Victoria Hand Project, *Nepal (arm prosthetic)*

Figure 2. Fixed production on-site at implementing organisation.

sustain this supply chain model. As such, they advocated for increased ownership at the local level.

> You want to empower that community to be able to start making things after you're gone… For it to scale, it can't be us shepherding it the whole time. At some point you want to transition and hand it off to that local community. (CS1-01)

Fixed production on-site at implementing organisation

In the second archetype (see Figure 2) there is a reduction in the number of upstream tiers through the disintermediation of international and local suppliers. Manufacturing takes place on-site at the implementing organisation, allowing for direct distribution of finished products to the end users.

The interviewees emphasised the importance of being close to the end users for producing customised designs, as well as creating trust and transparency in the supply chain.

> We realised you have to be printing in action. Printing remotely does not work, you have to be near the people. Not just to get more real time access, to get feedback on the designs, but also for gathering interest. People want to see what it is, want to see how it works. Otherwise it's just some voodoo, mystic, dark art that we are doing, trying to take their jobs away. So we started putting 3D printers in hospitals in East Africa in about five countries. (CS3-01)

Bringing production close to the end users eliminates the last mile distribution of finished goods and also helps to overcome supply chain issues associated with maintenance and repair.

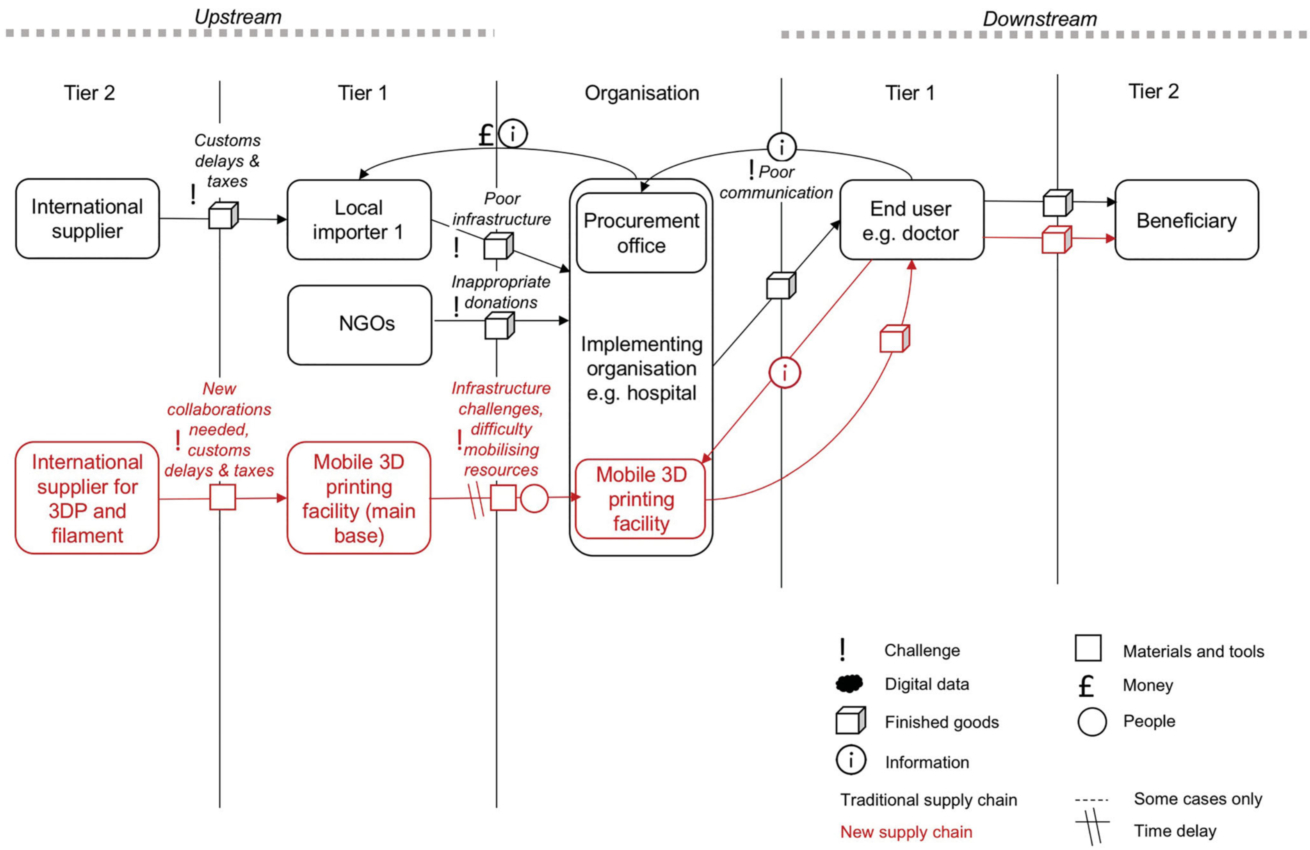
> It's fortunate that in Nepal the printers and the clinical staff were in pretty much the same building… If somebody comes in the clinic… it can be a quick repair right there… the clinical staff also has some knowledge of 3D printing, so they can print something off. (CS5-01)

Overall, 3DP reduces complexity in the manufacturing process, by reducing the number of process steps required. This can improve the delivery time of products to end users.

> It's good because it's a very quick process. Some of these people when they visit the clinic, they have to travel from outside of the city… You don't want them to have to be waiting around for a week to get a new prosthetic. It's ideal to later that day have the prosthetic done and be able to fit someone. (CS5-01)

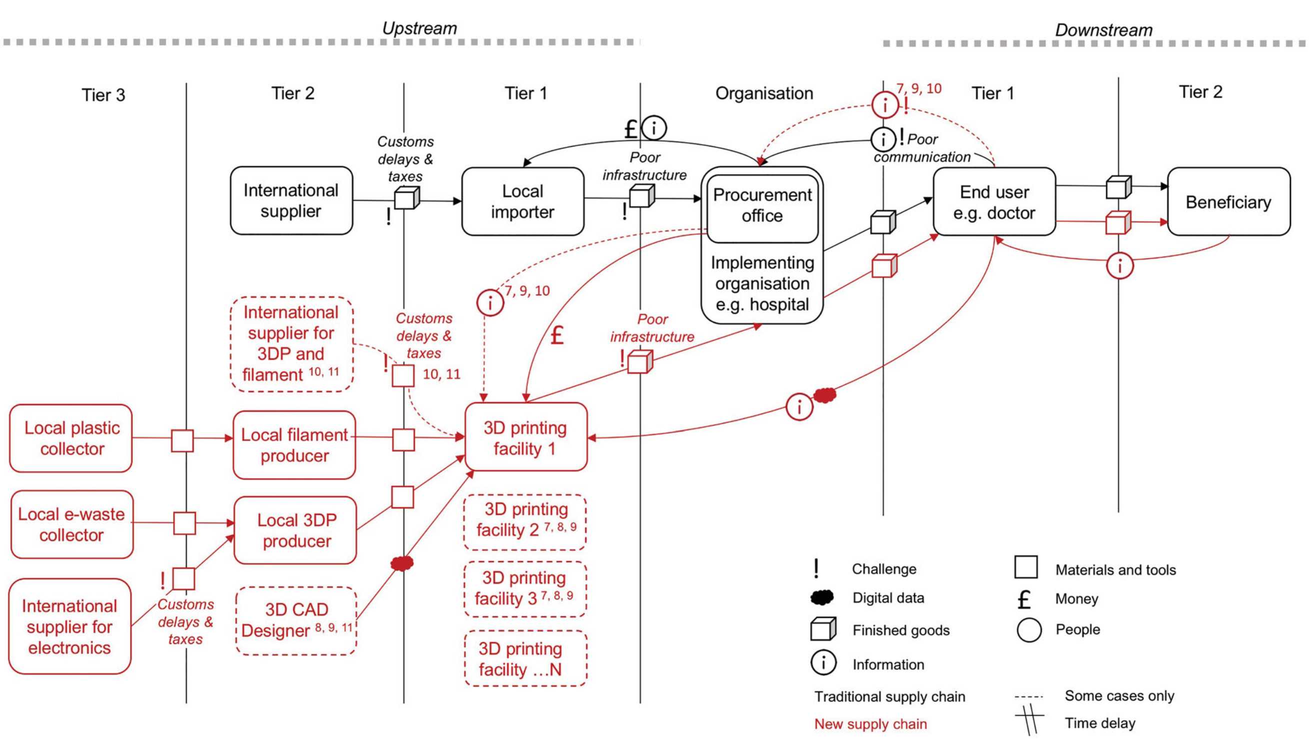
As the supply chain challenges of transporting finished goods decrease by placing the 3D printer further downstream, the challenges of supplying human capital and infrastructure capital increase as infrastructure is likely to be poorer or disrupted. All of the case studies using this model relied on importing 3D printers, filament and spare parts, which shifts the burden of importing finished goods to materials and tools.

> If a part does break on a printer, they won't be able to find that part in the country… Also not many people have used a 3D printer or the software we use… It's quite a learning curve. (CS5-01)



6. Field Ready, *Nepal (suction pump spare part)*

Figure 3. Mobile production facility at implementing organisation.



7. FabLab Nairobi/KNH Hospital/Concern, *Kenya (suction pump)*, 8. Glia, *Gaza (medical items)*, 9. IIT-B, *India (leg prosthetics)*, 10. MSF, *Jordan (arm prosthetic)*, 11. Victoria Hand Project, *Cambodia (arm prosthetic)*, 12. Waterscope/AB3D/STIClab, *Kenya and Tanzania (microscope)*,

Figure 4. Distributed production at local manufacturing hubs.

Table 2. Summary of key benefits and challenges of archetype one.

Key benefits	• Eliminates supply chain delays and taxes associated with importing finished goods. • Reduces warehousing and transportation of finished goods. • No recruitment or training of local design team required. • Easier to identify a secure space upstream from users with existing infrastructure (e.g. WIFI, electricity).
Key challenges	• Last mile logistics challenges transporting finished goods. • Recruitment or training of manufacturing staff. • Information sharing between international design team and local manufacturing team. • Importing raw material and production technologies

Table 3. Summary of key benefits and challenges of archetype two.

Key benefits	• Production is on-site, close to end users. • Facilitates quick user feedback, customisation and iterative design. • Eliminates supply chain delays and last mile distribution of finished goods.
Key challenges	• Finding/ creating a suitable facility with appropriate space (e.g. clean, temperature controlled) and infrastructure (e.g. access to WIFI, computer hardware/software, electricity). Investment cost of setting up a facility. • Recruitment and training of local manufacturing team. • Information sharing between international design team and local manufacturing team. • Importing raw material and production technologies.

Table 4. Summary of key benefits and challenges of archetype three.

Key benefits	• Production is on-site and close to end users, facilitating customised design. • Potential to respond to unpredictable and distributed demand. • Eliminates supply chain delays and last mile distribution of finished goods. • Limited requirement for human/ infrastructure resources at implementing organisation.
Key challenges	• Investment in a robust and versatile mobile facility. • Recruitment and training a flexible design and manufacturing team, who can travel to remote locations. • Importing raw material and production technologies.

Table 5. Summary of key benefits and challenges of archetype four.

Key benefits	• Design, manufacture and production of tools/ materials are localised. • Distributed production increases resilience and ability to meet spikes in demand. • Economic and social impacts from the development of a local supply chain. • If available, existing makerspace provides appropriate space (e.g. clean, temperature controlled), infrastructure (e.g. access to WIFI, computer hardware/software, electricity) and access to expertise. Less investment required to establish facility.
Key challenges	• Last mile logistics transporting finished goods to implementing organisations.

To mitigate the challenges of supplying human capital, projects leverage the capacity of distributed design teams based in the Global North. Whilst this overcomes the immediate challenge of training or recruiting a design team locally, it presents question marks for long-term sustainability. The case studies emphasise that local ownership is fundamental to successful collaboration.

> It's also recruiting regionally or locally so it's not all just on you… taking the time to make sure all the players are there creates something that's sustainable. (CS4-01)

New upstream relationships between the manufacturing and materials/tools producers reflect the potential for 3DP to foster new collaborations and add value across the supply chain.

> We started feeding back to some of the main suppliers … to say they [3D printers] are breaking down too frequently, they can't handle the fluctuations [in power]. So we actually got one of the companies to rewrite some of their Arduino code, so that if the power went off for a few seconds, the machine would then take the cartesian coordinates from the G-code. To date it's the only machine that can do that. (CS3-01)

Mobile production facility at implementing organisation

The third archetype (see Figure 3) uses a mobile production facility to supply 3 D printed items. Human resources, materials and tools (including renewable power supplies) are all transported to the implementing organisation, thus enabling production at remote locations with poor infrastructure.

This approach is suitable when demand is unpredictable or fragmented across different geographical locations. As design and manufacture needs to be completed in a timely manner, it is well suited to producing simple, one-off items such as spares and repairs.

> Cutting out those supply chains adds value for money and faster delivery… there's less wastage, there's less over-ordering, minimum order quantity is one. (CS6-01)

Unlike the previous archetypes, design takes place on-site, allowing for direct design and manufacturing. Not only does this reduce supply chain complexity, but it also facilitates more user-driven design that responds to contextual needs.

> We went to a remote rural health post to distribute some 3 D printed otoscopes… Then they showed us a broken suction pump… it had been damaged in transportation and so it had never worked, and we were able to fix it in half an hour. (CS6-01)

> Because you can customise further down the supply chain, you're able to do things which might mean a product that's more suited to the context. (CS6-02)

Despite eliminating the need to import finished goods, this model still relies on importing production tools and materials, and the mobile facility must be transported to local organisations.

> In Nepal, for instance, there's three people who can fix 3 D printers in the whole country .... If the machine that cuts out your supply chain issues depends on a massively complex supply chain to get spares, then you're kind of back where you're started, aren't you … We have to order all of the spare parts for the printers from China. It takes four weeks and there's a minimum order quantity, so we have to wait until we've got like $500 worth of spares that we need. (CS6-01)

It was also noted that although design is local in the sense that it takes place on-site, it often relies on 'importing' human capital. This underlines the point that local production means more than just printing items locally. There is a need for a holistic supply chain approach which builds on endogenous capabilities to include the local production of materials and tools, design and manufacture.

Distributed production at local manufacturing hubs

In the final archetype (see Figure 4) distributed manufacturing takes place at local manufacturing hubs or *makerspaces*. Design also takes place in-country and is shared with other makerspaces using digital communications. Finished goods are then transported to implementing organisations.

Distributing production helps to manage high volumes of demand across multiple facilities and mitigate against disruption.

> They're distributed because we expect at least one of the sites to eventually be bombed. (CS8-01)

Underlying this approach is the belief that local production can facilitate broader social and economic benefits. Organisations adopt this supply chain configuration not just to supply humanitarian items, but also to support local empowerment. Localising both design and manufacture supports participatory design that includes the end users.

> So we've tried to be very inclusive when it comes to getting more perspectives from different people … When you bring all of these angles together, then you end up with a very good idea that works for everyone. (CS7-01)

The manufacturing hub itself provides a 'knowledge centre' that helps to cultivate local skills.

> It's a wonderful place to work from [the makerspace] … You have a lot of people in there with design and engineering background and you can bounce ideas off them and get inspired by lots of different projects that they're working on. (CS10-01)

Compared with the previous archetypes, this is the most suitable approach for developing more complex and contextually appropriate products. Local design and production eliminates the challenges of maintaining and repairing imported devices, which often require additional expertise and lengthy supply chains to procure spares. The local hub or makerspace provides a secure, stable facility for long-term development of products that address the humanitarian needs associated with poverty.

> Equipment that has been designed in another country … may not work for us because we don't know how to maintain them. And getting our people to be trained on how to do that is also very costly because people have to be flown to those countries to learn … if we made them locally then it means getting spare parts would be very easy … if we buy a machine from a developed country and bring it here, they may not exactly make it or design it to be very resilient to a harsh environment. So once you bring it here and it meets very rough floors … or very harsh temperatures … it breaks down. (CS7-01)

In an effort to reduce dependency on international supply, the production of 3 D printers and filament is localised. Whilst some interviewees believed that imported technologies were more reliable, the people interviewed in this group highlighted that imported technologies were often expensive and unsuitable. For one organisation facing long-term supply chain disruption, recycling waste plastic to create 3DP filament locally was the only way to source materials.

> All of our plastic is recycled … Gaza is so blockaded we have a 100% recycle rate on plastic. (CS8-01)

> We found that machines were not appropriate for the environment, both in terms of their ability to withstand the environment, but also their ability to be maintained locally … 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 … figuring out how to take waste plastic and turn it into filament seemed to be a no brainer. (CS12-04)

Localising the production of 3 D printers and filament creates value across the supply chain and triggers the creation of new waste collection industries, therefore increasing supply chain circularity. Still, international supply is not completely eliminated as some electronic components cannot be sourced locally. Until the 3DP industry grows enough to warrant the creation of these industries locally, the challenges of importing items will still exist.

Finally, organisations adopting this approach should consider the distance between the manufacturing hub or makerspace and the end users. If a makerspace already exists close to demand, setting up production there provides a low-cost option that does not require significant infrastructure and human capital. The number of makerspaces is growing exponentially in the Global South, however they are mostly located in large urban cities. One organisation described the challenges of last mile distribution, when using a makerspace not in the local area. For highly customised products or products that require ongoing maintenance and repair, locating the production facility further downstream is clearly an advantage.

> There's the capital, Phnom Penh, and that's where the makerspace was, but the clinical staff were in Siem Reap, which is a five hour drive away … So there's this shipping of the plaster impressions, the prosthesis … I would spend almost every weekend having to drive up to Siem Reap and change supplies and everything … at least being in the same city would be much better. (CS11-01)

Discussion

There is a global mismatch in humanitarian demand and supply of aid. The industrial revolution created a global supply network that produced vast wealth for some, however excluded a large proportion of the world's population. Given the failure of traditional supply chains to effectively meet people's needs, humanitarian organisations have started looking at 3 D printing for new solutions.

It is generally predicted that 3DP will shorten existing supply chains (Holmström et al. 2016; Bogers, Hadar, and Bilberg 2016) and support more localised production (Tatham, Loy, and Peretti 2015; Shah et al. 2017). Our findings bring clarity to these broad statements, by revealing four archetypes that show how 3DP can drive more local supply chains in the humanitarian sector. Recognising local production as an umbrella term, our archetypes reveal that production can take place *on-site* (i.e. production at the location of end users), or *in-country* (i.e. finished goods do not cross a country border). Local production can also be *exogenous* (i.e. using 'imported' human capital) or *endogenous* (i.e. using local knowledge and skills). These differences have important supply chain impacts, and there is an urgent need to clarify this vocabulary in HSC research.

Broadly speaking, our findings show that locating a 3 D printer further downstream facilitates a more user-centred supply chain. In terms of governance, on-site production reduces information distortion in the supply chain (Lee, Padmanabhan, and Whang 2004) and supports new collaborative relationships downstream (Shah et al. 2017). Generally it highlights the move away from a push strategy to a more adaptive pull strategy (Wang, Chen, and Li 1996; Wong and Hvolby 2007). At the same time, it eliminates the last mile distribution challenges of finished goods. On one hand, moving the 3DP facility downstream maximises logistics benefits, but on the other hand, it creates additional burdens for supplying materials, infrastructure and human capital. Importantly, our findings recognise that there is no 'one size fits all' model and that depending on the type of product required (i.e. customisation, complexity) and the exact nature of the context (i.e. infrastructural capital, institutional capital and human capital), organisations may select different network configurations.

Whilst 3DP is facilitating the increasingly local production of humanitarian items, the majority of supply chains are still dependent on importing materials and tools. This is a concern as HSCs are often vulnerable to disruption and delays. Furthermore, the reliance on exogeneous design skills may undermine local knowledge and limit the development of contextually appropriate products (Papanek 1985). In this respect, the final archetype (*distributed production at local manufacturing hubs*) offers a potential model for self-sufficiency. Motivated by broader sustainable development goals, it adopts a totally local supply chain. Organisations seek to simultaneously meet humanitarian needs, whilst creating local employment through design and manufacture. Further environmental and economic benefits result from the local production of filament and 3 D printers, by upcycling waste into valuable resources. This demonstrates the potential of supply chain configurations for the circular economy (Masi, Day, and Godsell 2017). Given that vulnerable populations are more affected by humanitarian crises (Strömberg 2007), promoting the development of communities while responding to humanitarian needs creates a basis for improved recovery and preparedness (Otto and Weingartner 2013). Therefore we underline the need for a holistic supply chain approach to local production, that includes the: (1) production of materials and tools; (2) design; and, (3) manufacture.

Reflecting on our findings, we review the differences between 3DP-led HSCs and traditional HSCs. Our study has shown that 3DP offers significant advantages with respect to networks, governance, processes and products. However, we have also pointed out some of the key challenges of implementing these new supply chain approaches. Moreover, our findings suggest rather than replacing existing supply chains, and therefore eliminating complexity in the supply chain, 3DP often introduces an additional supply chain for organisations. 3DP cannot be a substitute technology for producing all humanitarian items. As a result we contest views that that 3DP will necessarily simplify the supply chain. Finally, one major advantage of centralised production is that it supports efficient quality and production control (Tatham, Loy, and Peretti 2015). It is beyond the scope of this study to compare the quality of the 3 D printed items in the case studies with their alternatives (in some cases there are no alternatives). However, we recognise that many practitioners found that their inability to guarantee the quality of 3 D printed items was a major obstacle to product implementation. There is an urgent need for new ways to manage decentralised quality control in HSCs, particularly as many applications relate to medical products or products used in clinical settings.

Lastly, we ask ourselves how do we expect 3DP to impact HSCs compared with conventional supply chains? So far, 3DP's impact on conventional supply chains has been relatively limited despite increasing speculation about the advent of a new production paradigm (Holmström et al. 2016; Bibby and Dehe 2018; Fatorachian and Kazemi 2018). In the last decade, conventional supply chains have become more centralised (Durach, Kurpjuweit, and Wagner 2017). In contexts where efficient supply chains exist, the desire to maximise economies of scale and out-source operations to countries with low labour costs has preserved the status quo (ibid). In HSCs, however, the same rules of the game do not apply. Life-saving products are required urgently, often with little advanced warning, and infrastructure is notoriously poor or disrupted (Heaslip 2018; Heaslip, Kovács, and Haavisto 2018). It is for these reasons that 3DP seems particularly advantageous for HSCs, and potentially more so than for conventional supply chains. As one of the first studies in this area, we therefore encourage other researchers to investigate 3 D printing in the HSC.

Conclusion

This paper has provided a much-needed examination of the impact of 3 D printing (3DP) on the humanitarian supply chain. Previous research in the field has been very sparse and academic research has failed to keep pace with progress in the humanitarian sector, being reported in the media.

Our research brings more clarity to this emerging field, by analysing multiple case studies of organisations using 3DP to produce humanitarian items. We revealed four supply chain archetypes that demonstrate the different ways that 3DP is impacting the supply chain with respects to: (1) network; (2) governance; (3) process; and, (4) product.

Our findings make important contributions to existing theory, as we reveal how 3DP is changing the humanitarian supply chain. Our findings question the assumption that 3DP will necessarily shorten and simplify the supply chain. Instead, we argue that to maximise the benefits of 3DP, a holistic supply chain approach is needed. In particular, we believe that local production of 3 D printers and filament is needed alongside local design and manufacture to create value across the supply chain. Practically, our findings point out the resources needed to implement these new supply chains, as well as some of the trade-offs that humanitarian organisations should consider when introducing 3DP into the supply chain.

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Appendix

Appendix Table 1. Overview of organisations.

Organisations	Product case study	Humanitarian scenario	Location of product implementation	Key informants	Archetype	Case study
3D4MD, Médecins San Frontières (MSF)	Medical items and spares	Poverty	East Africa	CEO and designer, 3D4MD (CS1-01) Project manager, MSF (CS1-02)	1	1
Oxfam	Hand washing device	Conflict	Lebanon	Project manager and engineer, Oxfam (CS2-01)	1	2
3D Life Prints	Arm prosthetic	Poverty	East Africa	CEO, 3D Life Prints (CS3-01)	2	3
Not Impossible	Arm prosthetic	Conflict	South Sudan	Project manager, Not Impossible (CS4-01)	2	4
Victoria Hand Project (Nepal)	Arm prosthetic	Earthquake and poverty	Nepal	COO, Victoria Hand Project (CS5-01)	2	5
Field Ready, World Vision	Suction pump spare part	Earthquake and poverty	Nepal	Programme manager, Field Ready (CS6-01) Design lead, Field Ready (CS6-02)	3	6
FabLab Nairobi, Makerspace, KNH Hospital, Concern Worldwide	Suction pump machine	Poverty	Kenya	Project manager, FabLab Nairobi (CS7-01) Project manager, KNH Hospital (CS7-02)	4	7
Glia	Tourniquets	Conflict	Gaza	CEO, Glia (CS8-01)	4	8
Indian Institute of Technology-Bombay (IIT-B), Ratna Nidhi Charitable Trust (RNCT)	Leg prosthetic	Poverty	India	Physiotherapist, IIT-B (CS9-01) Designer, IIT-B (CS9-02) Logistics manager, RNCT (CS9-03)	4	9
Médecins San Frontières (MSF), FabLab Irbid	Arm prosthetic	Conflict	Jordan	Project manager and engineer, MSF (CS10-01)	4	10
Victoria Hand Project (Cambodia)	Arm prosthetic	Poverty	Cambodia	COO, Victoria Hand Project (CS11-01)	4	11
Waterscope, AB3D, STIClab	Microscope	Poverty	Kenya, Tanzania	CEO and engineer, Waterscope (CS12-01) CEO and engineer, STIClab (CS12-02) CEO and engineer, AB3D (CS12-03)	4	12