



# Using digital fabrication tools to provide humanitarian and development aid in low-resource settings

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## 1. Introduction

The emergence of new digital fabrication tools is radically changing the way products are designed and manufactured [69,73]. According to Cross [19], design is a problem-solving activity that creatively meets people's needs. However, design practice and design research has largely failed to address the needs of people living in low-resource settings [4,71]. Recently, design for humanitarian and development aid is being given a new impetus by the growth of digital fabrication tools.

The benefits of new digital fabrication tools (3D printers, laser cutters and CNC mills) have been widely reported in the context of high-resource settings. However, it cannot be taken for granted that technologies can replicate successful designs from the developed world to the developing world [2,44,63]. As such, there is a need to investigate the benefits of these tools, specifically in low-resource settings (LRSs). Whilst anecdotal reports exist on the use of digital fabrication for developing solutions for humanitarian and development aid,<sup>1</sup> there remains limited understanding about how the benefits, challenges and opportunities of digital fabrication tools might be leveraged in LRSs.

This study intends to address this gap in knowledge by conducting a systematic literature review to explore the role of digital fabrication for solving humanitarian and development problems in LRSs. This article reviews and synthesises existing literature in order to: (i) list and review relevant design projects, offering key points of reference in the field; (ii) provide wider recognition for recently published articles, increasing their influence; (iii) present a framework to integrate learnings from different projects, reducing replication of effort; and, (iv) identify a future research agenda to expand knowledge in the field. For the first time, this paper attempts to move beyond reports of one-off design interventions to provide an integrated point of view that is useful for design practitioners and researchers.

The paper is structured as follows. First, a detailed description of the methods for the systematic literature review is provided. Second, a summary of the project interventions is provided, revealing types of

technology, sector and applications. Third, the key benefits, challenges and enablers associated with using digital fabrication tools in the humanitarian and development sector are explored. Finally, opportunities for using digital fabrication tools are discussed and implications for future research are outlined.

### 1.1. Research scope and key definitions

The research is limited to the digital fabrication tools associated with the *digital fabrication revolution* [33]. Within this definition, this study focusses on manufacturing technologies where finished components can be produced directly from digital models created in CAD systems: 3D printing, laser cutting and CNC milling.

The following study is framed in the context of European Parliament's report on *Linking Relief, Rehabilitation and Development* [27] which highlights the need for a more integrated approach to humanitarian and development aid. Humanitarian aid typically responds to a specific event or crisis, whereas, development aid is generally a response to systemic problems [74]. However, transitioning between humanitarian and development projects is a non-linear process [27] and the same products may be relevant in both sectors. Given this blurred boundary, this study explores the potential of digital fabrication in both humanitarian and development contexts.

LRSs are considered to be resource constrained environments, which typically have limited access to access to finance, infrastructure, services or expertise. More generally, LRSs are located in low-income or lower-middle income countries, as defined by the World Bank [92].

## 2. Method

### 2.1. Data collection

To better understand how digital fabrication tools are being used to solve humanitarian and development problems in LRSs, this paper takes

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<sup>1</sup> Several news articles have also been published, including reports on 3D printed prosthetics [9,12,52,64], medical supplies [37,46,84], shelters [34,94] and water and sanitation [32].

its evidence from a systematic literature review. This approach helps to identify any gaps in research and helps to build a framework to position future research. Based on recommendations from Kitchenham [50], this section explains the review protocol used for data collection and analysis.

To gather relevant papers, the following online international databases were searched: Scopus, Web of Science, IEEE Xplore Library for Global Humanitarian Technology Conference. Snowballing was also used to search references in papers to identify additional articles. Any short papers, posters, workshops and any non-peer reviewed papers were excluded from the search. All articles were examined up until 2018 (July). The key search terms were combinations of the following search terms: (“3D printing”; “laser cutting”; “CNC milling”; “digital fabrication”; “additive manufacturing”; “low resource”; “limited resource”; “developing countries”; “developing world”; “third world”; “humanitarian”; “emergency response”; “disaster response”; “disaster relief”). This resulted in 139 articles. In an effort to identify as many articles as possible, Google Scholar was also used. The first two pages of twenty-one Google Scholar searches were retrieved for screening. This resulted in a total of 559 articles for review.

## 2.2. Inclusion and exclusion criteria

After initial inspection, it was found that seventy-four papers were duplicates and these were removed. In an effort to identify relevant papers, the following inclusion criteria was defined:

1. The paper focuses on design for humanitarian or development aid in LRSs.
2. The paper describes the design outcome or design process of a physical product.
3. The paper describes a design produced using a digital fabrication tool (i.e. 3D printer, laser cutter or CNC mill).
4. The paper is peer reviewed.

In order to identify relevant papers, an initial title review was conducted, resulting in the exclusion of 437 papers. One hundred and ninety-seven papers were removed because they described the wrong context (did not meet criteria 1), e.g. “Exploring the use of additive manufacture for high value consumer products”. Twenty-eight papers were removed because they did not describe the design or design process of a physical product (did not meet criteria 2), e.g. “3D Printing with marginalized children—an exploration in a Palestinian refugee camp”. One hundred and ninety-five were removed because they did not use digital fabrication (did not meet criteria 3), e.g. “GIS technology for disasters and emergency management”. Finally, seventeen were excluded because they were non-peer reviewed (did not meet criteria 4).

This resulted in a total of forty-eight papers for abstract review. The remaining papers were subject to the inclusion criteria, based on a review of their abstract. Six papers were removed because they did not meet criteria 1, three papers were removed because they did not meet criteria 2 and eleven papers were excluded because they did not meet criteria 4. This resulted in a total of twenty-eight papers. After full paper review, a further eight articles were identified through snowballing. One non-peer reviewed result (a book chapter) was included because it was written by the same authors and described the same project as another key journal article. The authors noted that among the articles that met the inclusion criteria, six were retrieved from Google Scholar, providing support for using this database to complement widely recognised academic databases such as Scopus and Web of Science. In total, the review stage resulted in thirty-six articles (see Fig. 1).

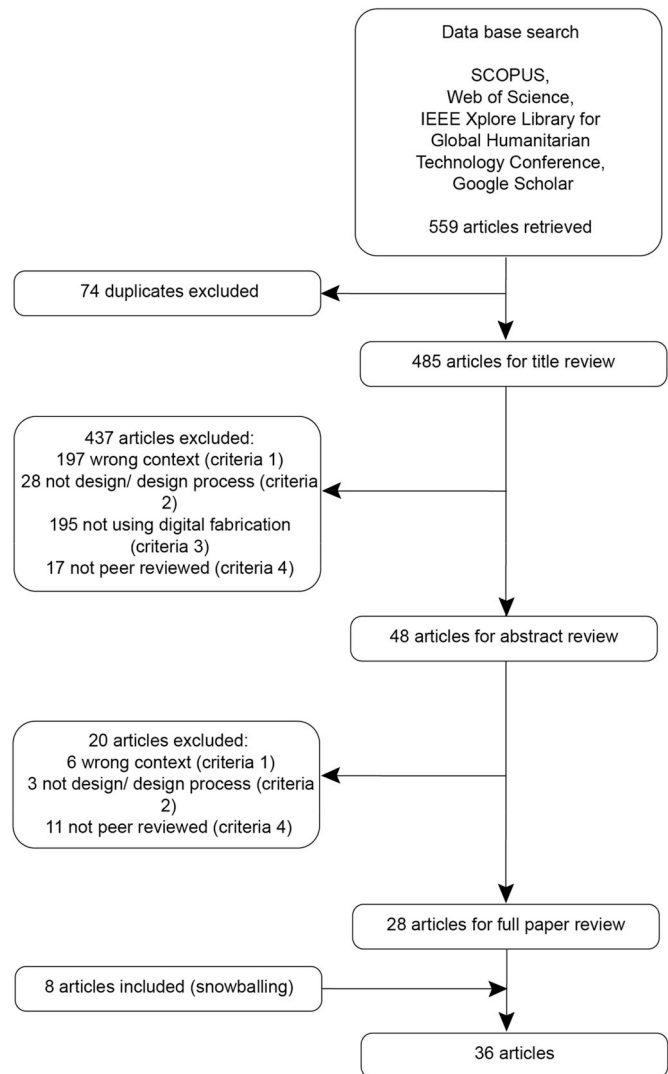


Fig. 1. Data base search method.

## 2.3. Data management

A data management protocol was adopted in order to ensure clear documentation of the data collection and analysis stages. Database results from the systematic literature review were recorded, and justifications for inclusion and exclusion of articles were documented. The body of literature identified from the systematic literature review was imported into the qualitative data analysis software, MAXQDA.

## 2.4. Data analysis

To begin with, an analysis of the articles was conducted based on the following: manufacturing technology used (e.g. 3D printing, CNC milling, laser cutting); application (e.g. prosthetics, shelters); sector (e.g. medical, architecture); focus (humanitarian, development or both); location; data collection method; data analysis method; and key conclusions. This analysis was conducted in order to characterise the types of projects undertaken.

Further analysis was conducted using MAXQDA to complete line by line descriptive coding. Initially, the first author used a first cycle of descriptive coding as a way to extract data from the literature [78]. Particular attention was focused on identifying key benefits, challenges and enablers associated with the use of digital fabrication tools. Descriptive coding provided a summary of the basic theme of a phrase or

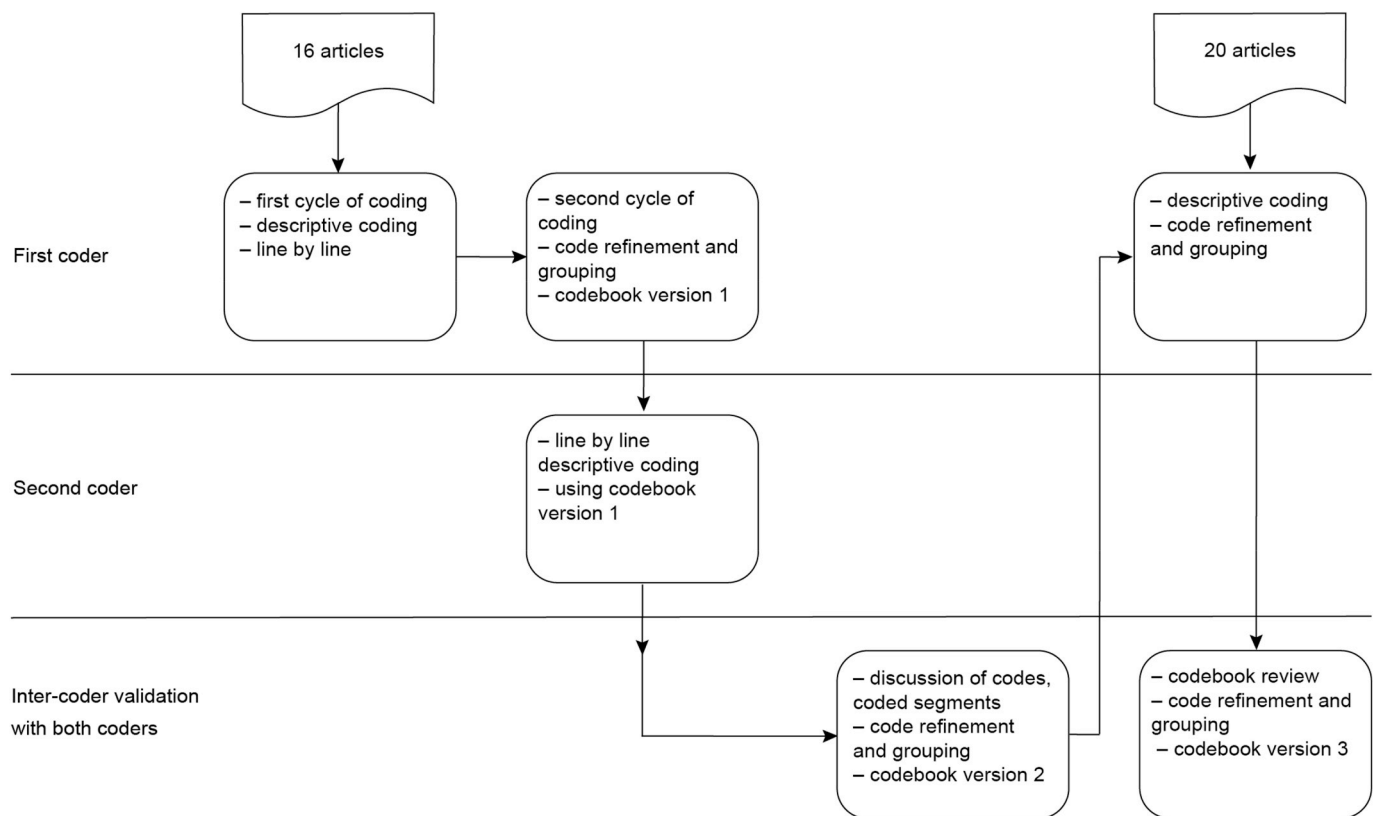


Fig. 2. Inter-coder validation method.

*coded segment*. On first iteration, there were 603 coded segments, coded against 85 codes. For example, the *coded segment*: “The benefits of this approach are made possible because the technology allows for the customisation of each 3D print” [54] was coded as *bespoke design*.

Following this, a second cycle of pattern coding was undertaken, in order to group major themes in the data [58]. During another iteration of second cycle coding, refinement and grouping produced a set of 81 codes. For example, in the first cycle of coding, the following coded segment: “The common 3D printers currently available in the market are still limited for printing small sized objects” [43] was coded as *limited build size*. In the second cycle of coding, the coded segment was assigned the higher-level code *design constraints*.

### 2.5. Inter-coder validation

Multiple coder qualitative research improves research reliability and quality [89]. For this study, a multiple coder research methodology was adapted from Berends & Johnston [10], as shown in Fig. 2. After the second cycle of coding had been completed for sixteen papers by the first coder, the MAXQDA file was shared with the second coder. An explanation of the code categories was provided along with a codebook, which provided a rationale for coding [55]. Independent coding of the sixteen papers was conducted by the second coder, using a descriptive coding approach.

Following independent coding, both coders met to intensively review and discuss the new codes that had been created, and reach coding agreement [39]. A qualitative approach was taken to review coder discrepancies in order to reach consensus [15]. None of the first coder's coded segments were changed indicating strong agreement, however, eleven new codes were created by the second coder. Taking a negotiated agreement approach, it was found that several of the new codes were either duplicates of existing codes, or that they could be effectively grouped with other codes. Following a second revision of the codebook, the coders met again in an attempt to further refine and

clarify the set of codes. To provide greater clarity, it was agreed to label codes using the following three labels:

1. Benefits of designing with digital fabrication tools in LRSs.
2. Challenges of designing with digital fabrication tools in LRSs.
3. Enablers that support successful design using digital fabrication tools in LRSs.

Each code was reviewed and discussed individually, and assigned one of the three labels. In the case that there were overlaps between codes, further grouping and refinement took place. The outcome of this discussion resulted in a reduction of twenty-four codes. The third version of the codebook included fifty-seven codes, referenced against 1095 coded segments.

## 3. Results

### 3.1. Type of research

For each article, the type of data collection and data analysis methods used were reviewed. With respects to data collection methods, it was found that twelve articles were proof of concepts; eleven articles were descriptive case studies; nine were technical tests; four were design interventions; two were literature reviews; and, two were usability tests. In some cases, articles were classified in more than one category. This reveals that most research is in an exploratory phase, focusing on developing and testing the feasibility of applications of digital fabrication tools. In contrast, there are few usability studies, signalling little understanding about user perceptions of digitally fabricated products and the long-term impacts of digitally fabricated products. In terms of data analysis methods, twenty-five articles use qualitative, descriptive assessments; twelve articles use quantitative analysis; nine analyse detailed designs; and, two articles present conceptual analyses.

**Table 1**  
Projects by sector, application and manufacturing technology.

Sector	Applications	Reference	3D printing	CNC milling	Laser cutting	Non-digital fab.		
Architecture	Shelters and assemblies	Botha & Sass [14]		X				
		Carlow & Crolla [16]		X				
		Griffith et al. [35]		X		X		
		Peinovich & Fernandez [68]			X	X		
		Yeung & Harkins [93]				X		
Medical	Medical tools and supplies	Baden et al. [5]	X					
		Belliveau [8]	X					
		Hafez et al. [36]	X					
		Ibrahim et al. [42]	X					
		Ishengoma & Mtaho [43]	X					
		James [45]	X			X		
		King et al. [48]	X					
		Pavlosky et al. [66]	X					
		Rismani & Van Der Loos [75]	X					
		Rogge et al. [76]	X					
		Saripalle et al. [79]	X					
		Wijnen et al. [90]	X					
		Zhang et al. [95]	X					
		Prosthetics	Prosthetics	Arabian et al. [1]	X			
				Belliveau [8]	X			
	Dally et al. [20]			X				
	Ibrahim et al. [42]			X				
	King et al. [49]			X			X	
	Maric et al. [57]			X				
	Nisal et al. [62]			X		X		
	Pearce et al. [67]			X				
	Phillips et al. [70]			X			X	
	Rismani & Van Der Loos [75]			X				
	Spare parts	Spare parts	Valencia et al. [86]	X	X			
			Zuniga et al. [96]	X				
De La Torre et al. [21]			X					
Ishengoma & Mtaho [43]			X					
James [45]			X					
Pearce et al. [67]			X					
Saripalle et al. [79]			X					
Schöning & Heidemann [81]			X					
Utilities			Communications tower	Stevens et al. [83]	X			X
				James [45]	X			X
	Cook stoves	Mok [59]	X			X		
		Rural electrification	Bassett et al. [7]	X				
			King et al. [48]	X				
Water and sanitation	Rainwater catchment	Pearce et al. [67]	X					
		Hafez et al. [36]	X					
	Water pipe fittings and connectors	Ibrahim et al. [42]	X					
		Belliveau [8]	X					
		James [45]	X			X		
		Loy et al. [54]	X					
Others	Disaster relief robot	Tatham et al. [85]	X					
		Chu et al. [18]	X					
	Germinator	Lacaze et al. [51]	X					
		King et al. [48]	X					

### 3.2. Technology used, application and sector

The review revealed that the majority of articles are focussed on 3D printing as a key technology, whereas a handful of articles consider CNC milling and only one article identifies laser cutting as a viable technology (see Table 1). The projects that consider CNC milling use the technology to achieve greater precision and strength in components than 3D printing might allow [62,86], or to produce larger scale products, such as assemblies or shelters [14,16,35,68]. Yeung & Harkins [93] use laser cutting to produce emergency shelters, but they identify that CNC milling could also be a viable production technology. Some articles recognise the potential benefits of integrating digital fabrication with non-digital fabrication tools. This is particularly true for medium-sized utility items such as cook stoves [45,59] and telecommunication towers [83]. Additionally, integrating 3D printed parts with standard parts allows for customisation while addressing some of the constraints of 3D printing. This approach is taken by King et al. [49] who recommends a hybrid production process using 3D printing and injection

moulding to produce prosthetics. 3D printing provides highly customisable design and injection moulding parts facilitates a more scalable and reproducible process. On the whole, however, there is a need for more comparison of digital fabrication with non-digital fabrication tools in future research.

Table 1 also shows that twenty-two out of thirty-six articles identify applications in the medical sector, with a large proportion of these focusing on prosthetic applications (12 articles) or medical supplies (13 articles). In these cases the use of digital fabrication is mainly motivated by the potential for customisation or logistics improvements through distributed, local manufacturing. A smaller number of papers (5 articles) explore the use of CNC milling or laser cutting for architectural solutions. Other applications of 3D printing focus on water and sanitation (5 articles); utilities (6 articles); spare parts (6 articles); and, general equipment (3 articles).

**Table 2**  
Product archetypes.

	Production of a standard part that is difficult to procure			6. Production of moulds or tooling for manufacturing
	1. Production of a highly customised product (each product is unique)	2. Production of a customised product (which is applicable to other contexts or combines custom parts with standard parts)	3. Part of a product	
	e.g. prosthetics	e.g. repairs	e.g. spares	e.g. mould for casting cook stove
<b>3D printing</b>	Arabian et al. [1], Belliveau [8], Daily et al. [20], Hafez et al. [36], Ibrahim et al. [42], Ishengoma & Mtaho [43], King et al. [49], Maric et al. [57], Nisal et al. [62], Pearce et al. [67], Phillips et al. [70], Rismani & Van Der Loos [75], Valencia et al. [86], Zuniga et al. [96]	Belliveau [8], Ibrahim et al. [42], Ishengoma & Mtaho [43], James [45], Mok [59], Pearce et al. [67], Rogge et al. [76], Saripalle et al. [79], Stevens et al. [83], Tatham et al. [85]	Belliveau [8], De La Torre et al. [21], Ibrahim et al. [42], Ishengoma & Mtaho [43], James [45], Pearce et al. [67], Rogge et al. [76], Saripalle et al. [79], Schönig & Heidemann [81]	Baden et al. [5], Bassett et al. [7], Belliveau [8], Chu et al. [18], Ibrahim et al. [42], Ishengoma & Mtaho [43], James [45], Lacaze et al. [51], Loy et al. [54], Pavlosky et al. [66], Pearce et al. [67], Rismani & Van Der Loos [75], Rogge et al. [76], Tatham et al. [85], Wijnen et al. [90], Zhang et al. [95]
<b>CNC milling</b>	Nisal et al. [62], Valencia et al. [86]	Botha & Sass [14], Carlow & Crolla [16],		Griffith et al. [35], Peinovich & Fernandez [68]
<b>Laser cutting</b>		Yeung & Hankins [93]		

### 3.3. Product archetypes

The characteristics of typical projects found in the literature are shown in Table 2. These types of project are presented as six product archetypes.

The first archetype is a highly customised product, where every product is unique. Examples of these products include prosthetics and custom surgical guides. Fourteen articles are included in this category. The second archetype is a customised product developed for a specific context, which may be applicable to other contexts. For example, Saripalle et al. [79] describe a bespoke fix for a dental chair, where the original part could not be replicated due to damage. In this case, the new product is customised, yet potentially relevant to other contexts. Similarly, Loy et al. [54] explore customised water pipe fittings, which are bespoke to locally available water pipes, yet potentially applicable to other contexts with the same water pipe dimensions. Fourteen articles refer to this archetype.

The next set of archetypes are standard products which are difficult to procure. These can be either a *part of a product* or a *whole product*. First, looking at the archetype part of a product, several articles identify that digital fabrication can be used to produce spare parts locally, where standard spares are difficult or expensive to procure. Nine articles identify this archetype. Whole products, on the other hand, can be simple (i.e. one digitally fabricated part) or complex (multiple digitally fabricated parts, which are possibly embedded with other components such as electronics). Ten articles describe simple, whole products. An example is a 3D printed umbilical cord clamp, found in Saripalle et al. [79]. In this case, digital fabrication is seen as advantageous because it enables on-site, rapid production of difficult to procure parts. Sixteen articles describe complex, whole products. For example, a partially 3D printed wind turbine, described in Bassett et al. [7]. This product includes multiple 3D printed parts, which are embedded with other non-digitally fabricated parts.

The final product archetype uses digital fabrication to produce tooling for mass manufacture. One of the limitations of traditional casting methods is that they require tooling, which can be expensive. Thus, digitally fabricated moulds remove this financial barrier, whilst supporting greater scalability. Only four articles consider this approach.

An archetype might be selected as an approach in order to achieve specific benefits related to customisation, logistics and cost. However, to achieve sustainable impact, a solution must be scalable. The question then follows, to what extent are each of these archetypes scalable? Considering that the scalability of a product depends in part on minimising its design and manufacturing time, for the first archetype, a product will be scalable if the design effort of customisation is low and the production time is low. Similarly, for the second archetype, scalability will be supported if customisation is quick and simple. This approach is particularly favourable if there is a significant need in other contexts. In this case, open source networks are important for sharing designs and avoiding unnecessary replication of effort. In general, the production of parts (archetype three) and simple, whole products (archetype four) present significant opportunities, as the design effort is low but the impact can be high. Here, the main limitation to scalability is production time, which is often balanced out against long supply chains. In the case of complex, whole products (archetype five), the design effort is considerably higher, however may be justified if the design is needed in multiple contexts and can be shared through open source networks. Finally, the production of moulds for tooling (archetype six) shows promise in terms of scalability, as this approach can be used to support mass manufacture.

### 3.4. Benefits of using digital fabrication tools in humanitarian and development aid

The benefits of using digital fabrication tools are grouped in three key themes: 1) Design and manufacture; 2) Supply chain and logistics;



**Table 3**  
Benefits of using digital fabrication tools in humanitarian and development aid.

Benefits	Mention by N articles
Design and manufacture	
Low-cost design	N = 28
Bespoke design	N = 27
Rapid manufacture	N = 15
Easy manufacture	N = 10
Improved performance (complexity, functionality, robustness)	N = 9
Easy assembly	N = 5
Precise design (replicable)	N = 4
Supply chain and logistics	
Reduced supply chain length (faster and more resilient)	N = 17
Reduced transportation (faster, less expensive)	N = 11
No warehousing and wastage	N = 9
Eliminate customs delays	N = 3
Social, economic and environmental development	
Local labour and capacity building	N = 14
Participatory design through prototyping	N = 11
Environmental savings (less materials, transportation savings)	N = 9
Market based development	N = 8

3) Social, economic and environmental development. The following section will discuss these themes in turn. N is the number of articles that identified the benefit, where the number of articles is taken as a measure of significance. Table 3.

#### 3.4.1. Design and manufacture

The benefit mentioned by the most number of papers (N = 28) is *low-cost design*. Clearly, in humanitarian and development contexts, affordability is a key constraint and the potential for digital fabrication to provide affordable solutions is a particular advantage. In particular, the use of open-source networks is identified as a way to minimise product development costs. For example, Pavlosky et al. [66] and Wijnen et al. [90] show that open-source 3D printing can be used to provide low-cost alternatives to expensive medical supplies and laboratory equipment. For most articles, however, this benefit is assumed rather than documented with evidence. Eight articles provide estimates for the cost of digitally fabricated designs, however they focus mainly on material costs, ignoring other costs [7,49,62,66,68,70,83,95]. Zhang et al. [95] provide examples of more detailed costings, which include electricity and material usage. In general, further research is needed to validate these low-cost claims. Specifically, whilst some studies might consider some of the ‘variable costs’, few studies account for the ‘fixed costs’ of supplying and maintaining the production equipment.

Related to the discussion of low-cost design, the literature highlights the important point that low-cost should not compromise product functionality or desirability. Pavlosky et al. [66] present a proof of concept design for a low-cost 3D printed stethoscope, with comparable quality to a standard stethoscope. They criticise the implicit assumption in the humanitarian and development sector that the provision of poor quality products is acceptable where no products are currently available. This highlights that low-cost design is not necessarily a driver for product success and that managing cost trade-offs is important when using digital fabrication tools for designing in LRSs.

The benefit of *bespoke design* is also mentioned frequently (N = 27). A number of papers identify the benefits of using 3D printing to produce customised prosthetics, medical supplies and bespoke repairs. Similarly, projects that explore CNC milling and laser cutting are also driven by the potential for greater customisation. In general, however, there is a need for more discussion about the trade-offs between customisation and scalability. King et al. [49] suggests that a hybrid production process using 3D printing and injection moulding to produce prosthetics might be adopted to address the limited scalability of 3D printing. In the case that every product is unique, the design effort

required for customisation should be low in order to achieve scalability. Wider applications for bespoke products should also be investigated. For example, a bespoke repair for a dental chair may also be suitable for dental chairs in other locations [79]. In this way, the initial design effort required for customisation can be justified. To increase the scalability of these bespoke products, open source networks could be used to share designs and avoid unnecessary duplication of effort.

A number of articles draw attention to design improvements that can be achieved when using digital fabrication tools, with respects to *complexity, functionality and robustness* (N = 9). This is noted alongside the potential for digital fabrication tools to produce precise and *replicable designs* (N = 4 articles). However, there is some conflict between these benefits and the reported challenges of using digital fabrication tools, which are also found in the literature: *design constraints and scalability and replicability*. Similarly, the articles highlight the benefits of *rapid manufacture* (N = 15), *easy manufacture* (N = 10), *easy assembly* (N = 5) as well as reporting the conflicting challenges of lengthy *production time* (N = 5) and need for specialist *training and support* (N = 12).

#### 3.4.2. Supply chain and logistics

The second major theme highlighted in the literature is related to supply chain and logistics. Digital fabrication supports local, distributed manufacturing capabilities, enabling a *reduced supply chain length* (N = 17). Shorter supply chains provide faster and more resilient responses to crisis and improve access to rural areas. Botha & Sass [14] describe the design for an instant house which uses CNC milling to produce flat pack assemblies for easy transportation to emergency and poverty stricken locations. Saripalle et al. [79] describe a number of case studies which use 3D printing to locally manufacture products, thereby reducing the need for transportation and eliminating the need for unnecessary warehousing costs. The benefits associated with supply chains are significant as challenges of ‘last mile distribution’ are repeatedly cited [21,45,54,85]. It is proposed that digital fabrication enables local production, thereby eliminating *customs delays* (N = 3), reducing *warehousing and wastage* (N = 9) and the *need for transportation* (N = 11), thus saving on cost and time to delivery. Further investigation is needed, however, to understand in which scenarios digital fabrication tools offer the greatest logistics improvements and where in the supply chain digital fabrication tools should be implemented to result in the maximum benefit. As Tatham et al. [85] note, placing a printer downstream would maximise the logistics benefits however, would create an increased need for training, maintenance and a reliable local source of raw materials and power.

#### 3.4.3. Social, economic and environmental development

A number of papers describe the potential for *environmental savings* as a result of using digital fabrication tools (N = 9). The literature identifies that potential savings may result from less material usage, reduced transportation and environmentally sustainable practices such as recycling filament and using solar-powered energy sources. It is noted however, that the articles mostly fail to evidence this. Only King et al. [48] and Zhang et al. [95] attempt to provide detailed analysis of material usage.

Other benefits result from supporting *local labour and capacity building* (N = 14). By creating distributed, local manufacturing capabilities it is possible to advance local skills and support economic development in affected communities. Ishengoma and Mtaho [43] highlight the potential for the economic empowerment of communities who engage with 3D printing to meet their own needs. James [45] highlights how this approach can combat the negative practice of ‘dumping’ international products on local markets. Instead, local manufacturing supports the resilience of local communities by maximising skills, technology and infrastructure. In this way, long-term benefits can be achieved through local economic development that provides solutions for local needs. This argument is related to *market*

*based development* (N = 8) which is defined as the use of digital fabrication tools to create new businesses and micro-businesses. Rogge et al. [76] describe two companies, STIClab and AB3D, in Tanzania and Kenya respectively, who have started small businesses to produce and sell 3D printed products. In this way, digital fabrication tools can support sustainable economic development.

Lastly, digital fabrication tools support rapid prototyping which facilitates more *participatory and iterative design* (N = 11). As Loy et al. [54] highlight, the potential for 3D printing to quickly produce one-offs allows for greater user feedback and engagement. In this way, designs can “evolve, rather than be imposed”. Similarly Rogge et al. [76] document that the ability to print microscopes on-site, on-demand allowed for customer feedback with little time or cost. Moreover, the potential for open, distributed manufacturing supports the participation of a global network of designers, engineers, users and other stakeholders. In this way, integrating digital fabrication tools with open-source and crowdsourcing models, can help to support iterative and collaborative solutions.

### 3.5. Challenges and enablers when using digital fabrication tools in humanitarian and development aid

The literature highlights a number of challenges and enablers associated with using digital fabrication tools in humanitarian and development aid. These factors are related to either the technology itself or the context it is used in. The following section will describe these challenges and related enablers in turn.

#### 3.5.1. Technology

**3.5.1.1. Design and manufacturing.** The challenge identified most often is *design constraints* (N = 19). These constraints are related to several factors, including size, material, tolerance, surface finish, strength, robustness. Notably, this factor is only reported in papers that focus on 3D printing. The 3D printing technology found in the literature is Fusion Deposition Modelling (FDM) and is therefore normally limited to the materials ABS or PLA. Clearly, these material properties may be inadequate for some applications. Another frequently observed constraint is the build size of 3D printing. In some cases, designs can be adapted in order to be printed and assembled in multiple pieces, however, in other cases, larger designs may be entirely infeasible. [Table 4](#).

In some instances, reported *design constraints* directly contradict reported benefits. For example, Ibrahim et al. [42] state that “3D printing offers the possibility of manufacturing precisely designed objects inexpensively and readily” and Hafez et al. [36] says that “it was found that the technology enabled manufacturers to produce high-value objects with accurate designing”. Furthermore, Arabian et al. [1] report that poor aesthetic quality of 3D printing is a source of prosthetic rejection whereas Zuniga et al. [96] report that the attractive aesthetic of 3D printed prosthetics makes them appealing. Despite these contradictory perspectives, it is clear from the number of papers reporting on the design constraints of 3D printing that this is a significant limitation. For products where size or material selection are important considerations, it recommended to consider using alternative technologies such as CNC milling or laser cutting. For these technologies, precise and regulated design is noted as another advantage [68,86].

Additionally, there are concerns about the *scalability and replicability* (N = 6) of 3D printing and its *production time* (N = 5). 3D printing is considered to be less replicable than CNC milling and laser cutting due to inaccurate prints, plastic warpage and machine malfunctions. The slow production time of 3D printing also presents challenges for scalability. Returning to the product archetypes discussed earlier (see [Table 2](#)), the design and manufacturing efforts should be minimised for each case to ensure that projects are scalable and sustainable. The archetypes fulfil different goals (customisation, low-cost and logistics benefits) but it is clear that some offer quicker wins in terms of

scalability. In particular, the production of parts (archetype three) and simple, whole products (archetype four) require little design effort but can potentially result in high impact solutions. Nonetheless, more complex solutions can be justified in terms of scalability, if the solution is widely needed and the design can be easily shared.

In response to these design and manufacturing constraints, three key enablers are identified. Several of the papers discuss *technological R&D* (N = 9), where the technological development of digital fabrication tools is seen as critical to overcoming design constraints. Another important enabler is *affordable production technology* (N = 18). The papers argue that digital fabrication tools will become more accessible as they become more affordable. In general the papers report that 3D printing is fairly affordable at present, however the affordability of CNC milling and laser cutting is not considered. Finally, the literature points out that *creating desirable outcomes* (N = 4) that users and consumers value will strengthen the demand for digitally fabricated products.

**3.5.1.2. Systems and infrastructure.** An important enabler for using digital fabrication tools in humanitarian and development aid is the *creation of design repositories* (N = 11). Design repositories help designers to leverage the benefits of open source and crowdsourced designs. Several articles identify this as a route to scalability, by expanding low-cost access. However, consideration needs to be given to managing *quality assurance* (N = 14) across these networks. Concerns around the replicability of 3D printing place additional burdens on quality testing. Moreover, the transition to local and distributed manufacturing raises new questions for quality and safety: how can quality standards be maintained across a distributed network of local manufacturing? How can open source designs be tested and verified?

The literature suggests that there is a need for *new certifications and tests* (N = 3) as well as *testing remotely and in-field* (N = 4). Loy et al. [54] put forward a proposal for a distributed hub-and-spoke model, whereby design and testing is carried out by a central team (the hub) and the design is shared with various communities in field locations (the spokes). Similarly, James [45] suggests an ‘open testing’ approach where communities of designers openly share test results of designs, providing validation through replication.

In order to facilitate this, an *ecosystem of designers and makers* (N = 7) is needed. Developing a community of designers and makers provides the skills and support necessary to facilitate design and manufacturing in a distributed network. Rogge et al. [76] report that TechforTrade is creating the Digital Blacksmiths Network to manage open source product development and improve access to training and tools. In addition, there is a need to *develop local capabilities* (N = 5) including the technology and supporting infrastructure for local manufacturing. For example, James [45] describes the development of a 3D printing facility in a health care centre. Developing local infrastructure and access to portable digital fabrication tools, such as those found in King et al. [48], may also help to overcome two challenges identified in the literature: *supply of production technology and infrastructure* (N = 7) and *supply of raw materials* (N = 4).

**3.5.1.3. General approach.** *Open source design* (N = 22) is identified as an important enabler for using digital fabrication tools in humanitarian and development aid. Open source design draws on international design communities to provide free access to design solutions. In contrast, *remote design and collaboration* (N = 10) is a more closed form of collaboration. This factor specifically refers to the placement of technically skilled workers from an organisation in different geographical locations, whereby remote design teams collaborate with local, in-field teams. This enables organisations to be close to users, whilst benefitting from globally available resources. Although there is little comparison of these open and closed models of distributed design, it is hypothesised that closed models will be easier to manage in terms of resource allocation and quality control, whereas open models present greater opportunities for scalability.

**Table 4**  
Challenges and enablers when using digital fabrication tools in humanitarian and development aid.

Focus	Challenges	Enablers
<b>Context</b>		
Environment and geography	Difficult access to end users (7) Power shortages (7) Problem complexity (7) Poor infrastructure (5) Harsh environmental conditions (4)	Renewable power (11) Recycled raw material (10)
Resources	Lack of resources for maintenance e.g. spares and tools (10) Lack of physical resources e.g. materials and tools (7)	Combine digital fabrication with local production methods and materials (9) Modular and reconfigurable designs (7) Stakeholder partnership and collaboration (7) Sustainable business models (5)
Economic, political and legal	Extreme poverty and financial constraints (6) Complex stakeholder environment (5) Lack of regulation and laws (3) Disrupted political environment (2)	
Social	Lack of non-physical resources e.g. people, skills, time (15) Cultural and religious factors (6) Communication and relationships (2) Employee turnover (2)	Training and support (12) Community empowerment and ownership (11)
<b>Technology</b>		
Design and manufacturing	Design constraints e.g. size, material, tolerance, surface finish, strength, robustness (19) Scalability and replicability (6) Production time (5)	Affordable production technology (18) Technological R&D (9) Create desirable outcomes (4)
Systems and infrastructure	Quality assurance (14) Supply of production technology and infrastructure (7) Supply of raw materials (4) Poor documentation (3)	Creation of design repositories (11) Develop technology ecosystem of designers and makers (7) Develop local capabilities incl. technology and infrastructure (5) Testing remotely and in-field (4) New certifications and tests (3) Open source design (22) Bottom-up and participatory design (12) Remote design and collaboration (10)
General approach		

(N) Number of papers that identify factor.

*Bottom up and participatory design* (N = 12) is highlighted as another enabler when using digital fabrication tools in humanitarian and development aid. By facilitating greater community engagement, it is argued that more sustainable projects will result. This ‘democratisation of technology’ supports the development of effective solutions.

### 3.5.2. Context

**3.5.2.1. Environment and geography.** The papers report several challenges related to the environment and geography found in operational contexts of humanitarian and development projects. The literature highlights the *problem complexity* (N = 7) of responding to humanitarian and development problems, which can include multiple, dependent challenges that are difficult to forecast and require immediate attention. Additionally the literature highlights that the widespread geographical location of people in rural and remote areas means it is *difficult to access end users* (N = 7). This is made further challenging by *poor infrastructure* (N = 5). Lack of adequate physical and telecommunications infrastructure is a significant barrier for supplying digital fabrication tools and raw materials. Moreover, *power shortages* (N = 7) including inconsistent or limited access to power, can disrupt production. *Harsh environmental conditions* (N = 4) also refers to difficult design, production and use environments. In particular, wind, heat, humidity and vibrations are noted as causing potential disruption to technologies, which are typically designed for high resource settings.

In response to these challenges, the literature reveals the enablers: *renewable power* (N = 11) and *recycled raw material* (N = 10). Notably, King et al. [48] explore two options for solar-powered 3D printing, considering community-scale PV-powered 3D printing and portable solar-powered 3D printing. Recycling material to produce 3D printing filament locally can be used to overcome the supply chain challenges associated with poor local infrastructure. As well as offering environmental benefits, this enabler supports the reduced cost of filament while adding value to local economy.

**3.5.2.2. Resources.** In LRSs, the *lack of physical resources* (N = 7) limits access to materials and tools. Likewise, the *lack of resources for maintenance* (N = 10) limits access to spares and maintenance tools. Both of these challenges are relevant to the technology (digital fabrication tool) and the outcome (digitally fabricated product). One suggestion for using digital fabrication in LRSs is to *combine the use of digital fabrication tools with local production methods and materials* (N = 9). Designing with locally available materials limits the reliance on physical resources that are difficult to procure. Additionally, this approach ensures that there are the skills and resources needed for repair and maintenance. By also using *modular and reconfigurable designs* (N = 7) it is possible to reduce the burden on repair and maintenance. This is important for digitally fabricated products and the digital fabrication tools themselves. Yeung & Harkins [93] note that digitally fabricated shelters should be designed in a modular way to accommodate changes in material availability. Rogge et al. [76] explain that the Retr3D printer has been designed parametrically so that it can be built using locally available resources, which may vary in dimension. The printer's modular nature also improves the cost and ease of maintenance.

**3.5.2.3. Economic, political and legal.** The literature reveals that the *complex stakeholder environment* (N = 5) typical of humanitarian and development projects can often be challenging. Additionally, *disrupted political environments* (N = 2) and *lack of regulation and laws* (N = 3) adds further complexity. It is reported that regulation may not exist, may be incomplete, ambiguous or of poor quality, making product compliance difficult. The papers identify that *stakeholder partnership and collaboration* (N = 7) is a key enabler to overcome these challenges. Notably, new stakeholder collaborations are needed to facilitate new models of distributed design and manufacture. For example, De La Torre et al. [21] describes a new approach to managing spare part supply chains, where manufacturers can directly share CAD files of replacement parts with local teams, in order to print spare parts locally.



This approach requires new partnerships between designers, manufacturers and clients.

With respects to economic factors, the literature highlights the challenge of *extreme poverty and financial constraints* (N = 6). This refers to the limited purchasing power of users living in LRSs, as well as the difficulty that solution providers (e.g. NGOs, social enterprises) face when trying to secure funding. Often organisations rely on funding from grants and competitions which are insecure or may prioritise limited types of projects. In particular, funding for testing, promotion and evaluation is often overlooked. In order to overcome this challenge, the literature suggests the need for *sustainable business models* (N = 5) that can meet humanitarian and development needs in the long term. James [45] suggests that the *Makernet* concept is one possibility for achieving sustainable business models. Makernet coordinates distributed manufacturing by connecting many small, local manufacturers with local market demands. To scale this network, there is a need for affordable product design and digital fabrication tools. Several papers observe that open source design facilitates affordable product design [5,35,66,67,90,96]. Additionally, Bassett et al. [7] and Pearce et al. [67] describe how the development of self-replicating digital fabrication tools supports low-cost expansion of technology access.

**3.5.2.4. Social.** The *lack of access to non-physical resources*, such as people, skills and time, is highlighted as a major barrier (N = 15) to using digital fabrication tools in humanitarian and development aid. This is also connected to the challenge of *employee turnover* (N = 2) which can be a particular problem in crisis-affected areas. On the whole, the literature assumes that the skills required for digital fabrication led interventions will be provided by external groups, either by international organisations or design networks. However, it is also pointed out that the development of local digital fabrication capabilities may offer greater benefits in the long term [54,85]. Specifically, Peinovich & Fernandez [68] explain that digital fabrication should not seek to replace but to advance existing, local skills. In addition, *community empowerment and ownership* (N = 11) allows people to take ownership of digital fabrication tools, which is a pre-requisite for bottom-up and participatory approaches. Supporting this user-driven design approach also helps to address the challenges: *cultural and religious factors* (N = 6) and *communication and relationships* (N = 2). In particular these tensions are found when aid providers, external to the local context, supply humanitarian and development solutions. Instead, developing local capabilities to develop solutions for local needs supports the design of more appropriate products.

#### 4. Theoretical discussion, research limitations and future research agenda

##### 4.1. Theoretical discussion

It is a common belief that technology will accelerate wealth production and reduce poverty [25,61,77]. Since the enlightenment, development has been viewed as the increasing complexity of technology, knowledge and society [17]. In line with this view, much of humanitarian and development aid has focused on importing foreign technologies to LRSs to address poverty.

In this study the design and manufacturing benefits associated with digital fabrication tools have been shown in the ability to produce highly customised, made-to-order products such as prosthetics, spares and repairs. However, the world's most urgent problems have not been solved [65] and many projects have failed because the technologies are not sustainable [23]. Clearly, technology is not a sustainable solution in itself, but it needs to be integrated as part of a social-cultural framework. The current study has considered both technological and contextual factors that impact the use of digital fabrication tools in LRSs for humanitarian and development aid. This builds on the view that appropriate technology is not neutral, but is contextual and situated

[2,63,65]. Consequently, appropriate structural changes and supporting infrastructure are needed to support the introduction of new technology.

The failure of traditional, centralised production to meet people's needs suggests that an alternative model is required. At the same time, the growing field of participatory design proposes that sustainable, long-term benefits are related to the autonomy of beneficiaries [26,60]. These ideas have generated interest in how local production can add value to local markets, therefore reducing dependency on imported goods and foreign aid [28,30,56]. To achieve this vision, local capacities must be developed that are not dependent on external technological support. This builds on the concept of *prosumption*, where individuals and communities produce what they consume [13,29]. It is suggested that digital fabrication might address the large number of people who are currently unserved by existing production and consumption systems. The rise of affordable, low volume production makes previously economically unviable markets accessible. Importantly, this moves away from paternalistic humanitarian and development aid models that focus on providing solutions [29,54]. Instead, communities are empowered to develop solutions for their own needs.

The potential for people to develop their own solutions in resource constrained environments is also found in literature on bricolage [53] and frugal innovation [71,72]. Precedent highlights how grassroots entrepreneurs can look beyond economic performance to address social problems in their communities. Although these groups can be market-driven, they are also motivated by socially-driven innovation [80]. Importantly, local production by local people overcomes the challenges of assessing the appropriateness of foreign products [23]. As well as providing triple bottom line benefits [24], local production has significant logistics and supply chain advantages. Specifically, this review has shown that shorter supply chains have the potential to provide faster and more resilient responses to crisis and improve access in rural areas. This specifically addresses the challenge of 'last mile distribution' that is highlighted in humanitarian and development literature [6,82,87].

Despite these benefits, local production is not necessarily suitable for all production. Hollick [41] points out that not all production should be decentralised, suggesting that it is not appropriate for regions with good communication and resource infrastructure for transporting goods. Hollick [41] draws on the work of Harper [38] who defines categories of items and highlights that centralised production is necessary for large scale industrial processes such as the conversion of ore into steel. Fox [30] conducts a more recent study of communities in West Africa and the Horn of Africa to understand which goods are appropriate for local manufacturing. The study reveals that appropriate products vary depending on local demand and supply. Clearly, the emergence of digital fabrication tools is expanding what was previously possible for local production, however it does not make centralised production completely redundant. For 3D printing, a number of potential applications have been identified including medical supplies, prosthetics, water pipe fittings, spare parts and utilities. For CNC milling and laser cutting, precedent shows that there is potential for the development of larger-scale shelters and assemblies. These applications suggest possible areas for product development, however the feasibility of their implementation requires further research, specifically in terms of product quality and safety. The literature review has also shown various product archetypes, which include the production of customised products, standard products which are difficult to procure and the low-cost production of moulds and tooling. These product archetypes are intended to show the various possibilities for using digital fabrication tools in the humanitarian and development sector.

##### 4.2. Research limitations

The literature included in this review significantly advances knowledge on the role of digital fabrication tools in the humanitarian

and development sector. However, it is noted that there are some deficiencies in the literature, which may limit research in this area. First, there is little comparison of the use of digital fabrication tools with other traditional manufacturing tools. This leads to concerns that people are incorrectly assuming that digital fabrication is superior because it is new and different. In some cases, there are apparent contradictions found in the literature as some papers refer to standard assumptions, without showing them with evidence.

Additionally, the majority of projects document designs without describing context-specific applications. Technology is situated in a social and economic eco-system [11,91] and the lack of contextual evaluation prevents a richer evaluation of project impact. Moreover, there is concern that the social dimension of sustainability is not being fully addressed in product development [40,47]. Mostly, the projects found in the literature are proof of concepts or technical tests, with only two papers conducting detailed user testing. In general, projects focus on design and production stages, with little consideration of product adoption and sustainability. The projects appear to be reports of one-off design interventions. The exception is Arabian et al. [1] who examine the long-term product adoption of 3D printed prosthetics. Whereas, short-term interventions have been largely criticised for failing to provide lasting impact and sustainable development [22], long-term design activities establish stable relationships between designers and communities, and typically have a clear purpose [88]. The applications found in the literature are typically reported as successful projects, however, more critical, longitudinal studies are needed to evaluate the impact of digital design and fabrication led interventions in both the short and long term.

#### 4.3. Future research agenda

This review has shown that there are a number of benefits associated with using digital fabrication tools in LRSs. It draws on arguments that low-resource settings should not be excluded from the potential advantages of new technologies [3]. However, until technological, quality and resource challenges are resolved, it is expected that most interventions will not scale beyond the provision of one-off solutions.

In order to achieve the goals of digital fabrication projects, several challenges need to be addressed. In terms of the design and technology itself, further technological improvements are needed for 3D printing to improve the printing speed, build size, accuracy, surface finish and material options. More affordable CNC mills and laser cutters are needed to improve access in resource limited contexts. Additionally, the quality assurance of distributed, digitally fabricated products remains a major obstacle. This draws attention to the need for new testing models to expand local, distributed design and manufacture. Furthermore, significant investment in local skills and capacity building is needed to overcome the gap in human resources found in LRSs. This is a prerequisite to community empowerment, bottom-up and participatory approaches. Specifically, the development of local digital skills is fundamental to ending the dependency of communities, which is reinforced through traditional humanitarian and development aid [61].

Future research should build on existing knowledge to define new ways forward. Fox [31] provides some recommendations for how to overcome the current skills gap using leap frog skills. These skills combine vertical skills, which increase productivity and consistency, with horizontal skills, which increase versatility. Additionally, further analysis of off-grid, moveable factories [30] could provide a potential solution for embedding digital fabrication tools in harsh environmental conditions. In this way, digital fabrication can represent a shift towards a more frugal industrial system [71].

Finally, future research should consider more long-term thinking and evaluation of product sustainability. Despite reports of successful projects, there is little evaluation of the impact of digitally fabricated products in use. In particular, longitudinal studies are required to

analyse the success of the applications highlighted in this review. This much-needed research will reveal the impact of digital fabrication tools on the wider social, economic and environmental ecosystem.

## 5. Conclusion

The current study explores how digital fabrication tools are being used in the humanitarian and development sector. A systematic literature review identified a wide range of applications of digital fabrication tools including, medical supplies, prosthetics, architecture, water and sanitation, utilities and spare parts. The review also revealed six product archetypes that describe different approaches for using digital fabrication tools in the humanitarian and development sector. These archetypes include the production of a highly customised product; a customised product applicable to other contexts; production of products that are difficult to procure (part of a product; whole, simple products; whole, complex products); production of moulds and tooling.

For the first time, this article integrates the perspectives of various design projects, in an attempt to move beyond reports of one-off design interventions. Analysis of the literature showed key benefits of using digital fabrication tools relating to: (i) design and manufacture; (ii) logistics and supply chain; and (iii) social, economic and environmental development. The challenges of using digital fabrication tools in humanitarian and development sector were also examined, with enablers for overcoming these challenges presented. Finally, opportunities for using digital fabrication tools were discussed and areas for further research were highlighted. In particular, the review highlights the need for greater evaluation of the long-term impact and social sustainability of digitally fabricated products in the humanitarian and development sector.

## Acknowledgment

The research is supported by funding from the UK EPSRC Doctoral Training Programme, grant number EP/L504920/1

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.techsoc.2019.02.003>.

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