Three dimensional printing – a key tool for the humanitarian logistician?

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Abstract

Purpose – 3D printing (3DP), which is technically known as additive manufacturing, is being increasingly used for the development of bespoke products within a broad range of commercial contexts. The purpose of this paper is to investigate the potential for this technology to be used in support of the preparation and response to a natural disaster or complex emergency and as part of developmental activities, and to offer a number of key insights following a pilot trial based in the East African HQ of a major international non-governmental organisation.

Design/methodology/approach – Using an illustrative example from the water, sanitation and hygiene (WASH) field this paper demonstrates, from both a theoretical and practical standpoint, how 3DP has the potential to improve the efficiency and effectiveness of humanitarian logistic (HL) operations.

Findings – Based on the pilot trial, the paper confirms that the benefits of 3DP in bespoke commercial contexts – including the reduction of supply chain lead times, the use of logistic postponement techniques and the provision of customised solutions to meet unanticipated operational demands – are equally applicable in a humanitarian environment. It also identifies a number of key challenges that will need to be overcome in the operationalisation of 3DP in a development/disaster response context, and proposes a hub-and-spoke model – with the design and testing activities based in the hub supporting field-based production at the spokes – to mitigate these.

Research limitations/implications – In addition to an extensive review of both the HL and additive manufacturing literature, the results of the pilot trial of 3DP in support of humanitarian operations, are reported. The paper recommends further detailed analysis of the underpinning cost model together with further field trials of the recommended organisational construct and testing of the most appropriate materials for a given artefact and environment.

Practical implications – 3DP has the potential to improve the response to disasters and development operations through the swift production of items of equipment or replacement spare parts. With low capital and running costs, it offers a way of mitigating delays in the supply chain through on site fabrication to meet an identified requirement more swiftly and effectively than via the traditional re-supply route, and it allows for adaptive design practice as multiple iterations of a product are possible in order to optimise the design based on field testing.

Social implications – The logistic challenges of responding in a disaster affected or development environment are well documented. Successful embodiment of 3DP as part of the humanitarian logistician's portfolio of operational techniques has the potential to deliver more efficient and effective outcomes in support of the beneficiaries as well as a sense of empowerment in relation to problem solving. In addition, it has the longer term potential for the creation of a new industry (and, hence, income source) for those living in remote locations.

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Originality/value – The research demonstrates that, whilst 3DP is increasingly found in a commercial environment, its use has not previously been trialled in a humanitarian context. The research reported in this paper confirms the potential for 3DP to become a game-changer, especially in locations which are logistically difficulty to support.

Keywords Humanitarian logistics, Additive manufacturing, 3D printing, Rapid manufacturing

Paper type Research paper

1. Introduction

The aftermath of a natural disaster or complex emergency requires those responding – be they national authorities, United Nations (UN) agencies or non-government organisations (NGOs) – to set up a supply network in which the goods and services necessary to meet the needs of the affected population are delivered as efficiently and effectively as possible. The extent and complexity of this network will depend on multiple factors, including the time available for action, the disaster size, its geographic and topographical context and the security environment (L'Hermitte *et al.*, 2013). Unlike the commercial context where product demand can, at least to an extent, be forecast in advance, the humanitarian logistic (HL) challenge reflects not only uncertainty over the timing of a disaster/emergency, but also the numbers affected (including the gender and demographic mix), the specific needs of the population (be these cultural, religious or related to the impact of current and future weather) and the accessibility of the location into which material needs to be transported (Kovács and Spens, 2007).

Given the resultant challenge of balancing supply against demand, humanitarian logisticians are actively searching for ways in which the overall process can be improved. One such approach is the use of 3D Printing (3DP) technology which has the potential to manufacture a particular item of equipment such as a spare part or component at a location that is close to the affected area. In doing so, it would avoid the delay incurred in obtaining the required item(s) from a remote location (be this in country or abroad), as well as achieving an improved logistic efficiency through the transport of a base material that can subsequently be used to manufacture a broad range of finished goods to meet an identified need.

2. Aim

The aim of this paper is, therefore, to investigate the potential for this technology to be used in support of the preparation and response to a natural disaster or complex emergency and as part of developmental activities, and to offer a number of key insights following a pilot trial based in the East African HQ of a major international non-governmental organisation.

To achieve this aim, the paper will begin by outlining the HL challenge. It will then, briefly, discuss the currently available 3DP technology as it relates to that which was deemed appropriate for the initial field trial. The next section of the paper covers the research methodology, together with a review of the literature relating to 3DP in an HL context, as well as the technology in general. Thereafter, an illustrative example of the use of 3DP to support the provision of water, sanitation and hygiene (WASH) services will be discussed in which the benefits and challenges are considered. This will be followed by a summary of the lessons identified from a pilot project to demonstrate the technology and obtain practitioner feedback from the staff of the African headquarters of a major international NGO. This, in turn, leads to a discussion of the most appropriate organisational construct that would support 3DP in the humanitarian context. The penultimate section will discuss the implications of potential developments of the technology before the paper ends with a summary of the discussion and proposals for the direction of future research.

3. HLs

As outlined in the introduction, the aftermath of disaster or complex emergency of any significance requires the development of a unique supply network that will either replace or enhance the pre-existing means of providing the affected population with food, water, non-food items (NFIs), medicines, etc. This is often achieved by the local authorities within the country or region but, in the case of major events such as the 2010 Haiti earthquake the 2013 Typhoon Haiyan in the Philippines or the 2015 Nepal earthquake, their efforts are supplemented by external assistance from a range of UN agencies and national or international NGOs (hereinafter referred to as "aid agencies"). The same basic scenario applies in a developmental context, where aid agencies typically assist the national government in the delivery of services such as drinking water, sanitation or medical support.

The resultant practice of HL has been defined by Thomas and Mizushima (2005, p. 60) as "the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements". Unsurprisingly, given that in 2013 alone 330 natural disasters were registered which affected around 100 M people with an estimated economic cost in excess of some US$120 BN (Guha-Sapir *et al.*, 2014), there is a significant drive to develop ways in which the efficiency and effectiveness of the HL preparation and response activities can be improved. Indeed, it has been estimated that HL operations (as defined above, i.e. procurement, transport into and within the affected country, warehousing and "last mile" distribution, together with associated activities such as information management) consume some 60-80 per cent of the income of aid agencies – i.e. some $US10-15 BN/year (Tatham and Pettit, 2010).

At one level, the HL challenge is somewhat easier than that facing a typical supermarket chain – not least as the number of stock keeping units (SKUs) involved is significantly less. For example, the catalogue of the International Federation of Red Cross and Red Crescent Societies (IFRC) contains some 10,000 items within three volumes, but of these two are devoted to medical equipment. Thus the NFI range is of the order of 3,000 SKUs – which can be compared to a typical supermarket which will manage some 40-45,000 SKUs (Fernie and Sparks, 2004; Ellickson, 2011). On the other hand, there are multiple challenges including the likelihood of significant damage to the telecommunications and physical (e.g. road and bridges) infrastructure, significant casualty levels, potential disruptions to the normal rule of law and the presence of the world's media and associated political and public interest (Kovács and Tatham, 2009). Not least of these challenges is the difference from the commercial context in which demand materialises by action of the shopper selecting items from a shelf (in a real or virtual sense), whereas the equivalent HL demand (i.e. the number of people affected, their location and their gender/age/culturally specific needs) frequently has to be assessed by the responding agencies as those affected are primarily focused on recovering from the disaster/emergency event.

With this overview in mind, it is almost inevitable that, to a greater or lesser extent, there will be a mis-match between the demand and supply situation. Furthermore, even if the original requirements were met, the challenging operating environment means that equipment breakdowns (e.g. to the operation of water pumping equipment) are inevitable, and the resultant requirement for spare parts etc., in effect, creates a fresh, unforecast, demand. One way in which this challenge can potentially be mitigated is through the use of 3DP technology which enables the manufacturing of a range of items at a location near where the piece of equipment is required – thereby responding to a demand that has actually crystallised. In other words, it offers close to the ultimate in logistic postponement (Christopher, 2011).

4. An introduction to 3DP technology

3D printing (3DP), technically known as additive manufacturing, refers to a range of technologies that build objects up in layers without the need for a mould or cutting tool. Although the concept of 3DP has been in existence for over 25 years (Campbell *et al.*, 2012), the development of new and improved technical solutions is changing what is possible to construct, where it is possible to construct it and also the number of an object that needs to be made in a given timeframe for the process to be economically viable. In effect, it offers a move from mass production to mass customisation.

3DP as a technology has been in commercial use as a prototyping tool since the early 1990s (Wohlers, 1995) and, indeed, has supported its own specialist academic outlet (the *Rapid Prototyping Journal*) since 1995. However, given that the technology for the delivery of 3DP for direct manufacturing, as distinct from prototyping, is fast developing this research perforce reflects the state of the industry at the time of writing (early 2015), although the penultimate section of this paper will reflect on the implications of emerging developments in this field. Nevertheless, as will be discussed at the end of this section, the underpinning principles, benefits and challenges remain the same whatever physical mechanism and medium is used to produce the required item of equipment. Whilst multiple 3DP technologies are already in use, this research discusses the use of "fused deposition modelling" (FDM) as this technology is ideal for use in printers that are mobile, low cost, easy to use on site and can utilise a range of source materials that would be suitable for creating products that can be used in a disaster or development environment.

When creating items using FDM, most basic level machines operate by heating a filament of material, usually a polymer, that is then extruded in a continuous feed (rather like a glue gun) whilst the bed of the machine moves slowly downwards thereby allowing an object to build. Such machines start at around the size of a desktop printer, and are easily transported. They are inexpensive with the lowest cost FDMs priced at < \$700 and, in line with "Moore's Law", the capability of such machines is growing at a fast rate whilst, in parallel, the cost for a given capability is reducing.

Single filament FDMs are the least problematic of the current range of printers to operate as they do not require a sealed print environment and can even be used outdoors if necessary – although wind strength and changes in humidity will affect them. They are not expensive to run with 1 kg of the filament for a portable FDM costing around \$40 – depending on the grade of the material. They are also the easiest 3DP to maintain, to make adjustments to on site and/or to repair if damaged in transit as the workings are accessible. An example of one such portable FDM printer in use as part of the pilot project (see Section 8) is at Plate 1, with the printer in its travelling box at Plate 2.

This relatively simple system can build complex objects using, for example, an engineering grade polymer called acrylonitrile butadiene styrene (ABS) which is typically used for the housings of electronic equipment such as computers and, indeed,

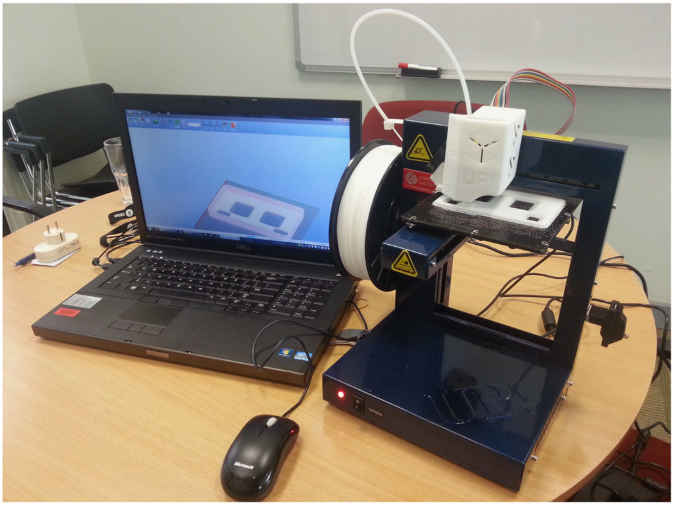


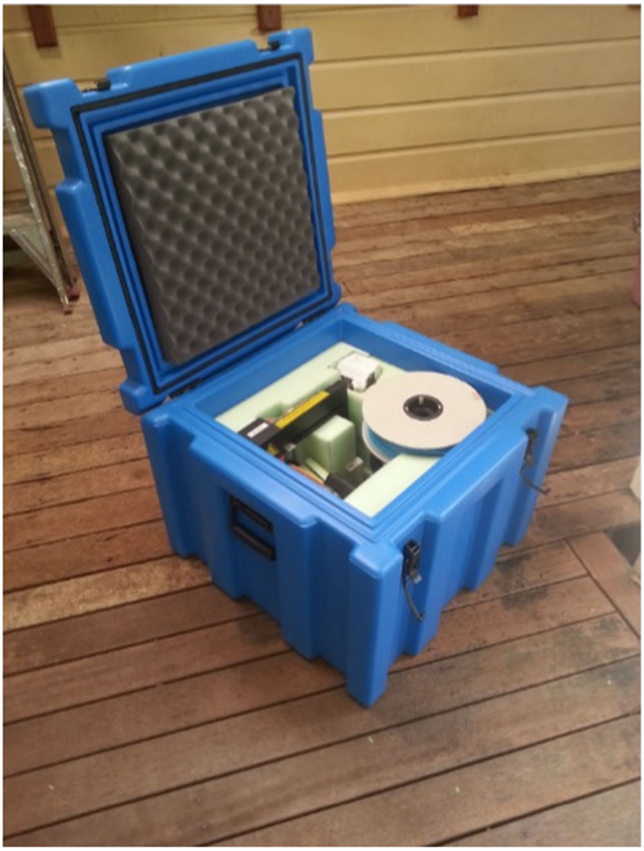
Plate 1.
Photograph of a portable FDM printer in use in the pilot trial location

Source: The Authors

LEGO blocks. It is a thermoplastic, which means it can be reshaped with heat – hence its suitability for FDM. Its mechanical properties vary with the relative proportions of its constituents and the temperature where it is used, which would clearly be a consideration in the HL context. Furthermore, whilst the specific plastic for each application would be chosen on a case by case basis, ABS is a fairly strong and reliable material which is, therefore, suitable as a starting point for initial applications in the HL context. However, as will be discussed further in Section 11, the actual choice of material will need to reflect both the operation of the component and environmental factors such as the ambient temperature range.

Beyond the capabilities of the machine itself, the practical support aspects of the technology will need to be addressed in relation to the context for use. The consistency of the power supply, for example, needs to be taken into account. This factor again points to the use of a desktop FDM in that any interruption to the power supply will cause the print to fail but not compromise the machine itself. That said, a dedicated mini-generator would create a reliable power source if persistent interruptions to supply were likely – such as is potentially the case in a post-disaster or developmental scenario. If the machine is to be used in an area where there may be vibrations such as aftershocks, then the open filament 3DP is the most suitable as the software includes a pause button which allows the print head to be stopped mid-print until the event has past.

The other key support aspect of 3DP is in relation to the 3D modelling software. Where the operator is simply creating a new item to replace a damaged part using an existing 3D CAD model, the process would be relatively straightforward. However, it may be more complex where a pre-ordered item proves unsuitable due to unforeseen circumstances. If the field operator is not a skilled 3D computer modeller, and given that access to the internet may be limited or not be available, the operator will need to be able to manipulate a part for a specific situation independently. There will, therefore, need to be a library of parts that include the facility for adjustments to be made without recourse to technical support. This can be achieved using parametric modelling, that is 3D computer models built using relationships instead of dimensions



Source: The Authors

Plate 2.
3D Printer in its purpose-designed travel container

that work within a strict set of control parameters developed by an industrial designer. In addition, the industrial designer would need to provide clear guidelines about the applications for which the material and printed objects could be used safely and reliably. The implications of this challenge, and the proposed solution, are discussed further in Section 9.

5. Review of the literature

Given the potential benefits of 3DP in support of the HL challenge as outlined above, an analysis of the relevant literature was undertaken. Unsurprisingly, there is a wealth of material relating to the operation of such systems in a commercial context with the available materials ranging from titanium to human cartilage (Cohen *et al.*, 2014), each area of which supports multiple publications and associated reviews of the literature. These, typically, describe recent developments in the particular context – for example, Negi *et al.* (2014) outline the basic operation of the technology, together with multiple applications within the field of medicine. In addition, there are multiple practitioner contributions in a broad range of publications including the "McKinsey Quarterly", IEEE Spectrum and DHL's Logistics Trend Radar. Whilst the actual figures offered in these publications differ, there is near complete agreement that the global market for 3DP will grow with DHL (2014) suggesting that the rate will exceed 10 per cent/year from some US$1.8 BN in 2012 to US$3.5 BN in 2017. Indeed, McKinsey forecast a market of $550 BN by 2025 (Cohen *et al.*, 2014).

Importantly, recent research into the use of 3DP has seen a shift in emphasis from consideration of the technology as supporting conventional manufacturing practices to its role as a disruptive technology. The seminal work on additive manufacturing, "Additive Manufacturing Technologies" (Gibson *et al.*, 2014), discusses the consequential changes in the business models needed for organisations to maximise the opportunities the technology provides and, in doing so, highlights the need to take into account transport costs, digital distribution methods, customised design and manufacturing. These issues are particularly relevant in HLs applications, and will be discussed further in Sections 6 and 8.

Given the growth in the use of the technology in multiple contexts, it was perceived that there is no a priori reason why 3DP should not be used in a humanitarian context. The literature in this field was, therefore, considered, first through an inspection of the most recent reviews which are to be found in Altay and Green (2006), Kovács and Spens (2007), Natarajarathinam *et al.* (2009), Pettit and Beresford (2009), Overstreet *et al.* (2011), Caunhye *et al.* (2012), Kunz and Reiner (2012) and Leiras *et al.* (2014). In this regard, it will be noted that the latter is the most comprehensive, and yet it uncovered just 228 papers that had been published in the last 20 years. A further source, the informal bibliography contained on the HUMLOG Institute[1] web site was also analysed using the titles of the works contained therein as the key to further review of the specific paper.

This initial review was unable to identify any academic research that specifically focused on the use of 3DP in an HL context. A second review was, therefore, carried out based on Kunz and Reiner's (2012) methodology in which the following databases were searched: Science Direct (Sci Dir), ABI/INFORM Complete (ABI), Business Source Complete (BSC) and Web of Science (W of S) using the keyword and Boolean operator string: ("Additive Manufacturing" OR "Rapid Prototyping" OR "Rapid Manufacturing" OR "3D Printing") and ("Disaster response" OR "Emergency Response" OR "Humanitarian Logistics"). The raw number of publications returned from this search is shown in the Table I below.

Of the above, an initial inspection showed that four papers were duplicates and, notwithstanding the search string, a further 11 were not in any way relevant. In addition, a significant number of publications were related to the use of 3DP in a medical context – for example, for the manufacture of prosthetic limbs (e.g. Thilmany, 2010), and the design of communications systems. Whilst clearly of great relevance in the humanitarian context, these were excluded from further consideration due to their specialist nature. Thus, after such papers were removed, a total of eight papers were identified for further analysis. However, an inspection of the content of these demonstrated that none discussed the potential use of 3DP in an HL context.

In the absence of literature that offers prior insights into the potential use of 3DP in this context, the next section describes that authors' analysis of the benefits that its use might be able to deliver. These theoretical observations were then reviewed by a

Table I.
Results of the database search

	Sci Dir	ABI	BSC	W of S	Total
Publications	56	37	4	2	95

number of practitioners, with the results shown at the end of this section. This was followed by a pilot trial in which the conceptual approach was exposed to a large group of humanitarian practitioners, the results of which are to be found in Section 8.

6. The potential for the use of 3DP in a disaster/development context

Based on a review of the general 3DP literature (see, e.g. Campbell *et al.*, 2012) and the general supply chain management/logistics literature, and in the absence of any specific mention within the HL literature, a number of theoretical benefits and challenges have been deduced, and these will be discussed in the following sections. It will be noted that the identified benefits fall into two generic categories: those that relate to the saving of logistic time and cost by the local production of an item to meet an identified need; and those that reflect the potential to meet an unanticipated or unexpected requirement by the creation of a novel item of equipment or, alternatively, one that incorporates novel features that are not easily created using standard injection moulding (or similar) techniques.

6.1 Benefits

Considering first, those benefits that are related to logistic savings, 3DP allows the manufacture of a range of items at or near the location in which it will be used. This has the potential to save significant time by obviating the need to order, and subsequently transport, the item from an external source (e.g. for delivery from one of the UN Humanitarian Response Depots). Whilst there is no firm data available in relation to such transit times, informal discussion with field-based logisticians (see Table II below) would indicate that one to three months between the ordering and delivery of items that cannot be sourced locally is not unusual. This elapsed time includes that necessary to achieve customs clearance which can be lengthy – for example Durgavich (2009) suggests that delays of up to six months for some countries have been encountered, whilst 70 per cent of respondents in a recent Organisation for Economic Co-operation and Development/World Trade Organisation survey reported that there were delays in customs clearance when importing goods (Shepherd, 2013).

Second, the use of a single raw material (such as ABS) from which multiple items can be created to meet an identified need avoids the requirement to transport items into the affected location "just in case". This has the potential for significantly more efficient

Role	
Head of logistics for an international NGO	UK
Technical advisor for an international NGO	UK
Head of logistics for an international NGO	UK
Field logistician for an international NGO	Australia
Head of WATSAN for an international NGO	UK
Field-based WATSAN engineer for an international NGO	Kenya
Head of logistics for an international NGO	Australia
Head of logistics for an international NGO	Australia
Head of logistics for an international NGO	Malaysia
Field-based logistician for an international NGO	Solomon Islands
CEO of a humanitarian engineering training organisation	Australia
COO of a 3PL operating in the humanitarian space	Australia
CEO of an NGO specialising in air transport	Australia

Table II.
List of practitioner respondents

transport – for example, through the movement of reels of polymer that require limited packaging and have a high mass to volume ratio, rather than finished goods (Macharis *et al.*, 2014). This latter approach can be seen as a classic example of the concept of "postponement" in which the value adding stage of, in this case, the production process is delayed until the demand has been identified (Christopher, 2011). The advantages of such an approach have also been emphasised by Waller and Fawcett (2013) who reflect on the potential for the use of 3DP in a military logistic context which has considerable similarities with that of HL (Kovács and Tatham, 2009; Tatham and Rietjens, 2015).

Turning to the second category, for historic reasons, there may be incompatibilities between the equipment supplied by different NGOs. In this respect, the work of de Leeuw *et al.* (2010) in support of the UN WASH cluster is instructive. In common with other such "clusters" (which include logistics, camp management and telecommunications), the WASH cluster aims to provide coordination across multiple elements of the UN family that provide similar services (in this case, water and sanitation, etc.). NGOs are also encouraged to engage with the cluster as a means of achieving improved coherence, efficiency and effectiveness. As explained by de Leeuw *et al.* (2010) one of the WASH cluster's aims is to develop a global stockpile sourced from and funded by multiple NGOs and agencies. Unfortunately, however, the current situation is that equipment provided by one organisation may not be compatible with that provided by another – for example, through the presence of different pipe bore sizes and/or screw thread arrangements. Thus, 3DP would potentially be able to produce a suitable item of equipment that can overcome such challenges which are difficult to forecast (and hence pre-position the relevant items) in advance.

Finally, the use of 3DP allows the design of components that are not constrained by the limitations of traditional mass production techniques. For example, it is relatively simple to incorporate in line filtration using an FDM machine, whereas this is challenging to achieve in the case of parts produced by injection moulding. By the same token, the provision of parametric computer models that can be adapted to meet a specific requirement leads to further potential benefits from a 3DP system.

6.2 3DP meets HL: an illustrative example from the wash field of operations

As part of the development and review of the proposed use of 3DP in a disaster or development context, it was considered essential that the concept be framed in a way that would clearly demonstrate how the theoretical benefits described above could be operationalised. The aim of this sub-section is, therefore, to show how this might be achieved through the use of an illustrative example.

Within the overall HL literature, there is a general acceptance that supplies fall into one of three categories: food items, NFI and medical items. Whilst there are examples of the use of 3DP within the catering industry, such applications tend to be in the area of novelty goods including those made of chocolate and/or coloured icing sugar (see, e.g. Chavez, 2014) and are, therefore, not appropriate for the disaster/development context. By the same token there is a wealth of emerging applications within the medical sphere (Gibson *et al.*, 2006), but these tend to use much more sophisticated technology than the FDM technique that is proposed and will, therefore, not be considered further.

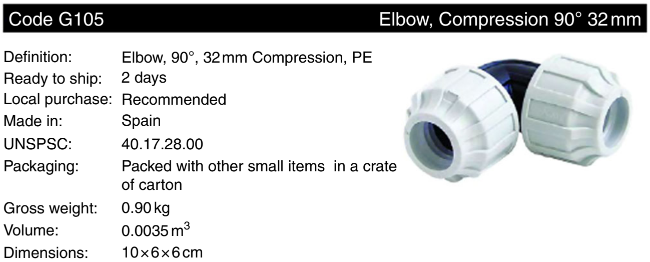
As indicated earlier, the IFRC catalogue contains some 10,000 items within three volumes, one of which is dedicated to food/non-food (as distinct from medical) items. The range within this latter volume covers items from warehousing via power supplies and electrical equipment to vehicles. Whilst theoretically, almost any item of NFI equipment could be manufactured using 3DP – including vehicles and houses – there is an obvious need to avoid developing unrealistic expectations. Thus, in the initial stages of the development and use of 3DP in a humanitarian context it is clear that the focus should be on meeting specific relatively low technology needs. For example, one of the informants at an earlier stage of our research suggested the following as potential artefacts that might be suitable for 3DP: a simple, fool-proof "gadget" that holds the plastic sheeting of emergency latrines (or shower stalls) shut ensuring privacy and a feeling of safety for the latrine users; a theft-proof soap holder or dispenser for use outside public latrines; and a replaceable and cheap latrine hole cover hinge mechanism.

In selecting a scenario that could illuminate the potential benefits of 3DP, the advice of the practitioner group (see Table II below) was sought. The overwhelming recommendation was that any future research should be based around the area of WASH for a number of reasons. First, the requirement for WASH is ubiquitous in both disaster and development contexts. Second, the equipment involved is relatively low tech and, for example, generally does not involve high pressure systems – and, hence, this helps to mitigate the safety concerns discussed above. Third, as discussed earlier, the existence of multiple variants of sizes, screw threads, etc. as a result of poor coordination of procurement by various agencies and donors means that there is a frequent requirement for bespoke parts.

Given that Oxfam is a world leader in the WASH field, the catalogue of this organisation (Oxfam, 2013) was used as the source reference. Within the "water" section, there are sub-sections relating to pumping (ten kits); storage (18 items or kits); distribution (13 items); and associated fittings (43 items), and in each case a "kit" contains multiple components. As an example, Figure 1 shows the entry for a right angle pipe connector.

Such an elbow joint could have its end components easily 3D printed on a small FDM using ABS. If, for example, the end component arrived on site cracked then it would be straight forward to call up the STL (this is the file name for a 3D printed part in a format ready to print) from a library supplied on disc, load it into the machine and print it. Printing such a single end piece, complete with screw thread, in ABS (which would be suitable for its purpose), took approximately four hours during trial runs using a small desktop, open filament printer. It may not require support material as the angles of the ascending faces are not steep, and so it could be used immediately without any finishing procedures required.

It is also technically possible to print the three separate parts (as in the original shown at Figure 1) with integral screw threads and different materials – for example, the central section is made from a rubber material. This represents an emerging development as it has only become possible to print with a rubber-like material such as thermoplastic polyurethane on a small FDM machine, such as being considered for use here, in 2014. Furthermore, such an item would need to go through appropriate standards testing before



Code G105	Elbow, Compression 90° 32 mm
Definition:	Elbow, 90°, 32 mm Compression, PE
Ready to ship:	2 days
Local purchase:	Recommended
Made in:	Spain
UNSPSC:	40.17.28.00
Packaging:	Packed with other small items in a crate of carton
Gross weight:	0.90 kg
Volume:	0.0035 m^3
Dimensions:	10×6×6 cm

Figure 1.
Elbow joint specification from the Oxfam catalogue (Oxfam, 2013) with kind permission of Oxfam GB

use. However, 3DP is not a straight forward substitute technology and, rather than making a direct copy, the part could be completely redesigned with fewer manufacturing constraints – although these most definitely do exist and need to be taken into account. This means that it may be possible to redesign the part to work more effectively, or to integrate additional functionality through the creation of internal geometries that are not possible with injection moulding – for example, to provide filtration capabilities within the pipe.

In addition, and most significantly, 3DP allows for an object to be altered and printed as a one-off component to suit an individual situation. For example if, when the 90 degree bend item shown in Figure 1 came to be fitted, there was a complication that meant the angle of bend should be 80 or 120 degrees, then a single new object could be 3D printed to meet the new requirements exactly. This would be particularly useful if linked to a parametric computer model where the user could make simple changes such as to the angle of the bend on an ad hoc basis.

Using 3DP, the three component object shown could be printed as one part as the manufacturing constraints would not be the same. However, unless a multiple print head machine was employed, the material used would then be the same for all three sections and this would require performance testing and standards compliance. Alternatively, as discussed above, it may be possible to redesign the object completely for 3DP in a way that adds value by improving performance or enhancing its functionality.

In summary, and reflecting the two generic benefits of the use of 3DP discussed above, from a logistic perspective it is estimated that the complete new part could be manufactured by a 3DP in less than half a day. This reflects a considerable time saving over the one to three months that would be needed to obtain a replacement item from outside the affected country or region. Second, from an industrial design perspective, there is potential for incorporating additional functionality and also the possibility of producing bespoke items (such as those needed to interface between equipment supplied from different sources), which provides further advantages over traditional manufacturing approaches.

6.3 Challenges to the use of 3DP in a humanitarian context

In terms of the challenges, these can be grouped under two headings. The first relates to the production process itself, and the second to the operator/maintainer. Thus, as indicated earlier, whilst the operation of a 3D printer is relatively simple in benign conditions, it will clearly be necessary to ensure that a suitably robust power supply exists, and that the necessary computing interface (including the parametric models) is available. Furthermore, the physical environment may impact on the quality of the finished product as wind, vibration and humidity all have the potential to interfere with the production process and the selection of the base material to be used.

More importantly, however, is the need to ensure that an item that has been produced by the use of 3DP is fit for purpose. For example, if the item is required to operate in a system that uses high pressure then a catastrophic failure has the potential to cause serious injury of even loss of life. It will be critical, therefore, to ensure that suitable safeguards are put in place to ensure that any items produced through the 3DP process can safely be used in the particular operating context. In terms of the man/machine interface, it will be necessary to develop suitable training courses that enable the transfer of knowledge to local personnel. These would need to cover both the basics of operation as well as, more importantly, ways to ensure the subsequent safe operation of the equipment (i.e. the “fitness for purpose” issue described above).

7. Moving from Theory to Practice

In order to ascertain the practicality of the above proposals, and in addition to academics in Australia, Europe and the UK, the concept was reviewed with a number of practitioners as shown in Table II. These were selected by "snowball sampling", a technique where the initial reviewers suggest other individuals from among their acquaintances to act as additional respondents. In each case, a copy of the draft journal article was provided and this was subsequently analysed in a telephone conversation and/or e-mail exchange with the respondents. Their input was then incorporated into a revised version of the paper.

As will be seen from the following excerpts from the e-mails, there was good support for the proposed use of 3DP:

> [xxx] says this [3DP] is exciting and they already had some plans of their own in this area. I take it this means that he'd be interested in talking about [NGO] taking part in the research.
>
> I think this is a really interesting project and am interested to see how it goes.
>
> I will push as I think it's a good idea.
>
> There have been discussions in the [xxx] Department over the last year about the possible use for 3-D printers. The most enthusiastic input has been from the Public Health Engineering team; first in discussing the possibility of making spare parts in the field and secondly, and more practically, in their use in new product design.
>
> 3D printing is an area we are tentatively exploring so your proposal is something of interest to us.
>
> As you may know I am sceptical that 3D printing is going to be transformational for humanitarian responses, but it could offer some benefits and [the proposed research] would explore potential uses.
>
> I am particularly interested in the 3DP idea. Let's discuss further as it would be good to try to test.
>
> Between the WASH program in the region with cross-cutting sectors (emergency food security and livelihood, protection, gender, etc), I would say we can find an application or two for the 3DP!
>
> The technology is really interesting and I believe it has huge potential in some of the areas we work in. It will be great to see the end result of your project, and I wish you all the best!

In short and without exception, these individuals expressed considerable interest in the proposed use of the technology and were immediately able to grasp the potential it offered for improvements in logistic efficiency/effectiveness. Furthermore, they were able to confirm that, to the best of their knowledge, the technology was not being currently used by any of the major aid agencies. That said, whilst there was considerable support for further investigations into the feasibility and practicality of the use of 3DP in a disaster/development context, several respondents indicated a healthy degree of scepticism over the extent to which the theoretical concept could actually be operationalised in an HL environment, citing concerns such as the implications of a lack of a stable power supply.

8. The results of a pilot trial of 3DP in a humanitarian context

Following confirmation from the expert panel that the use of 3DP had clear potential in a humanitarian context, the next stage of the research was to undertake a pilot project to confirm this initial view. This was achieved by deploying a researcher together with a printer for two separate 30 day periods to the headquarters of Oxfam

GB in Nairobi, Kenya. This HQ provides support to field operations in multiple countries stretching from Nigeria to Sudan. This element of the research was funded by a grant from the Humanitarian Innovation Fund, together with matching support from Griffith University, RedR (Australia) and HK Logistics plc.

During the first deployment to Nairobi, the researcher demonstrated the 3DP process to some 150 individuals ranging from the head of Oxfam's team to the office cleaners! A presentation was also made to the regional WASH cluster meeting that was attended by some ten to 12 aid agencies and NGOs. During this period multiple items of WASH related fixtures and fittings were printed (see Plate 3) and it can be seen that the 90 degree bend item (Plate 3a) is, in effect, a replica of the exemplar item from the Oxfam catalogue (see Figure 1).

The reaction of the audience was broadly similar on each occasion, and can be summarised as follows:

(1) initial healthy cynicism regarding the benefits of this "gee-whizz" technology;

(2) amazement at its capability which was amplified when the robustness of the printed products was demonstrated by means of a "drop" (or, perhaps more accurately a "throw") test; and

(3) a subsequent "light bulb moment" when the potential and implications of the use of 3DP were appreciated by the audience.

In particular those attending who were primarily engaged in WASH activities were particularly impressed by the robustness of the product and the absence of a "curing" time – i.e. the component could be used straight from the printer.

In subsequent discussion, two important points were raised. The first was that, in addition to the benefits described in Section 6.1 which were strongly supported, it was noted that, especially in the context of complex emergencies, there are protracted customs delays in relation to the items that could be imported. It was perceived, therefore, that the use of 3DP had the potential to mitigate these. The second was a concern that, particularly in a context where religion features significantly, it was possible that some

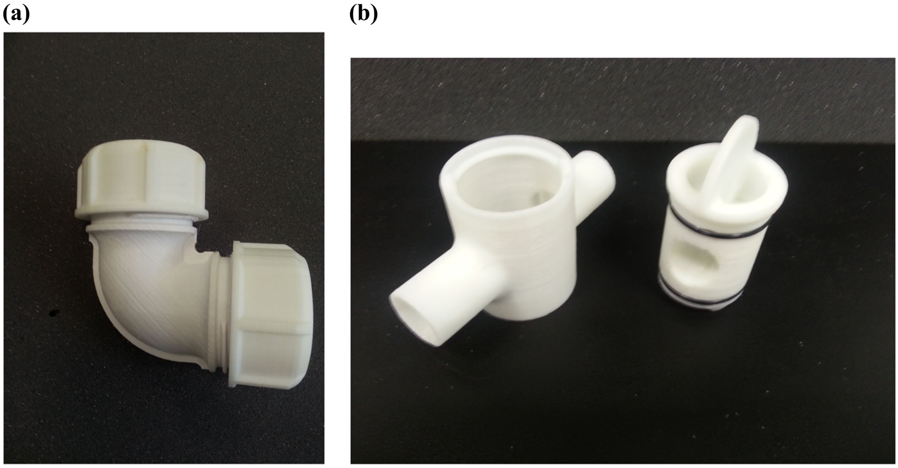


Plate 3.
(a) and (b) Examples of WASH fittings produced by 3D Printing at Oxfam GB HQ in Nairobi

Source: The Authors

might see the use of 3DP as “doing God’s work”. Clearly this latter point must be carefully considered as the use of 3DP moves forward.

In relation to the estimated lead time for items produced by the normal processes, an analysis of representative data provided by the Oxfam logistics staff indicated that the typical time between the placement of a purchase order and the delivery of the item to the Oxfam warehouse in Nairobi was 14 days for locally procured items and 50 days for those supplied from overseas. However, to these times must be added the delay between the request being made by the field staff and the creation of the purchase order (estimated at one to three days) and the delivery time from the warehouse to the field location (estimated at 14 days). Thus, the original estimate of a lead time of one to three months (see Section 6.1) has been confirmed.

In addition, the pilot research also underlined the potential technical challenges inherent in the use of 3DP. First, in the case of WASH equipment, the standard sizes (which relate to the diameter of the pipework) are 32, 63 and 90 mm. The printer used for the trial has a maximum print volume of 110 × 110 × 140 mm and thus, while entirely capable of replicating parts in the 32 mm series, was not really sufficient to support printing of items in the larger sizes. Second, complex items – even those destined for use in the smaller size pipes – can take in excess of ten hours to print. Whilst this is a lengthy time period, it should of course be compared with the one to three months that Oxfam staff indicated is the typical lead time for re-supply from their UK warehouse. However, in a field location, it is understood that the local power generators are typically changed over every eight to ten hours. Thus, during the changeover period, there is no power for a period of up to 30 minutes. The implication of this is that either the 3D printer needs to be supported by a dedicated power generator that is able to run for the duration of the print run – which may well not be achievable – or that some form of battery/uninterrupted power supply must be provided to cover the power outage.

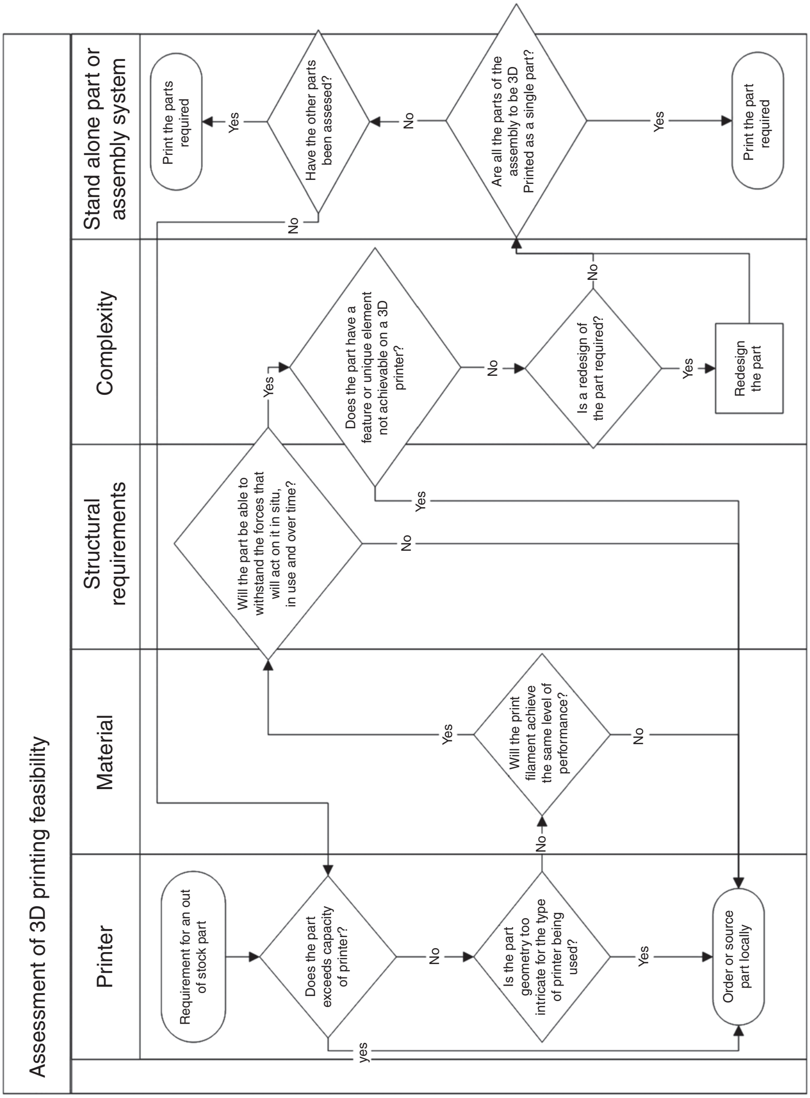
As a result of this pilot trial, an initial flow chart has been developed as a means of screening requests for items that individuals propose be printed by the 3D process and this is shown in Figure 2. The flow chart also, in effect, provides guidance to aid agencies who may be considering the use of 3DP in terms of the areas of key benefit and challenge.

The final and most significant issue that surfaced from the trial was that of the management interface between the design and production processes, and this will be discussed further in the next section where a proposed solution is offered.

In summary, and notwithstanding the challenges identified above, the pilot research clearly confirmed the potential of 3DP and also confirmed that the posited advantages discussed in Section 6.1 that had been drawn from an analysis of the commercial literature were, indeed, applicable in the humanitarian context.

9. Management of the 3DP process in a humanitarian environment

As indicated in the discussion of the pilot project (see Section 8 above), one major area surfaced during the research – namely the most appropriate way of ensuring that the printed component was “fit for purpose”. In other words that it is, for example, sufficiently robust structurally to take the working pressures etc. to which it will be subjected whilst operating. In reality, the authors were aware in advance of the trial that this was almost certainly going to prove an important challenge, however no mitigating action was taken as it was considered necessary to ensure that this was, indeed, an important issue that needs to be addressed going forward – as has proved to be the case.



Source: The Authors

Figure 2.
Initial screening of a request for a 3D printed component

Given the need to avoid any health and safety issues and also to ensure the maximum efficiency and effectiveness of the printed component, the challenge here is to ensure that whatever is produced by the 3DP process is truly fit for purpose. In this regard, the authors were supremely conscious of the potential for a well-intentioned individual to print a component that subsequently failed causing death or injury to field staff or beneficiaries. With this in mind, there are two basic approaches that could be implemented. The first is to provide the local staff with the necessary knowledge and skills to that they can alter a generic computer model in order to create a non-standard item that overcomes the problems identified during fitting or operations.

Adopting this approach has two implications. First, it will be necessary to ensure that the associated computer files are either pre-loaded with the specifications of the range of items that it is likely to be called upon to manufacture or, alternatively, arrangements would need to be made with the original equipment manufacturers to supply these at short notice. Second, the provision of such a 3DP facility for the support of field operations would require a system in which the field worker can access and adapt the basic model on site and then test the parts that have been manufactured in this way. It follows that there would need to be considerable planning and development in providing a useable system for non-specialist field workers to properly exploit the potential of 3DP.

The alternative approach is that of using a hub-and-spoke organisational construct in which the design and testing is conducted centrally, leading to the printing of a proven design at the spoke or field location – albeit local testing to ensure that the printed part is, indeed, fit for purpose will still be necessary. Based on this approach, the hub would be responsible for the design of the item to meet the field requirements and the subsequent laboratory-based testing of the output. Once tested in the hub, the data package will be transmitted to the spoke where a duplicate item will be printed and locally tested. Whilst simple in concept, it will be important to understand, in particular, the training/education needs of the operators at the spoke for this approach to be successful.

10. The way ahead for 3DP

As indicated earlier, this paper has been developed throughout 2014 and it is thus based on the state of the art at that time. However, the technology is rapidly evolving with a myriad of developmental directions that include the use of multiple print heads for increased speed as well as the production of complex multi-material parts, lower cost metal printing techniques and improved quality control within more clearly defined standards (Campbell *et al.*, 2012). The emergence of: large-scale 3DP for architecture (including house construction); nano printing; 3DP incorporating electronics; and major developments in 3DP with bio materials that are compatible with the human body, are all clear indictors of the potential of this technology to significantly disrupt current design, production and business practice across multiple disciplines.

The use of 3DP could be further enhanced by the parallel use of 3D scanning which would enable the field operator to identify and document the requirement swiftly and accurately, thereby simplifying the work of the design team. The facility will be explored during the next phase of the research work, alongside the development of information gathering tools for field operatives and interrogation of individual applications for underlying principles for decision making in the choice and redesign of suitable parts. Currently the team have developed an in-house manual to support selection of parts to adapt based on factors that relate to the engineering science impacting the design of the part for in use function over time, such as water pressure and exposure to the elements.

This will be refined and tested to provide the basis for the development of the library of items to be designed and modelled.

In parallel, and as noted by Waller and Fawcett (2013), the low cost of 3DP machines is leading to the development of third party design shops in which items can be manufactured to order and this is a significant emerging change in business practice. Whilst the current production time for an item can be measured in hours, this will unquestionably reduce and as noted by Campbell *et al.* (2012, p. 256) in a "for profit" context: "If fabrication speed is increased, parts will become available in minutes rather than hours. Consumers would be prepared to wait this short time for their parts to be made over the counter. Machines are likely to be seen in shopping malls and other locations where consumer parts can be made to order". Thus, if/when the technology is available even more widely, it is highly likely that such design shops will begin to flourish as part of a nation's economy – including in developing countries. This, in turn, may obviate the requirement for a dedicated machine (and operator) to be deployed as part of a post-disaster/emergency response or in a development context as it would enable the use of local equipment and/or locally sourced base materials with concomitant avoidance of the shipping costs of raw materials and benefits to the local economy.

11. Summary and areas of further research

This overview of the use of 3DP in an HL context has outlined a number of areas of potential benefit:

1. in avoiding the transport and warehousing of items to the relevant location that are subsequently not required (logistic efficiency improvement);
2. through the local manufacture of items to meet an identified need thereby avoiding the lengthy procurement and transport (postponement, leading to logistic efficiency improvement);
3. through the use of a source material that does not require special packaging and/or handling, and has a high mass:volume ratio (logistic efficiency improvement);
4. by overcoming potential delays imposed by customs and other authorities on the import of humanitarian goods (logistic efficiency improvement);
5. in the production of bespoke items that are not normally part of the standard inventory (be this held locally or remotely) (design improvement);
6. by introducing benefits (such as in line filtration) which cannot easily be created using mass production (injection moulding) techniques (design improvement); and
7. in the longer term, the use of 3DP has the potential to provide a most useful source of employment (and income) in remote locations (development improvement).

From a financial perspective, the initial capital cost is relatively small (< $700 and reducing), as is the cost of the raw material (some $40/kg and also reducing). On the other hand, maximising the capability of a 3DP system would require a significant investment in the training and education of staff at both the hub and the spoke, together with investment in the development and acquisition of the necessary parametric models and development of the associated performance testing and standards compliance regimes.

Such considerations clearly highlight the next stages of the research. First, it is essential that a robust analysis of the actual costs of the operation of a deployed 3DP facility in comparison with the alternative of a conventional supply chain is undertaken. Second, the proposed hub-and-spoke model must be tested in representative conditions in order to understand the training and education requirements at both the hub and the spokes, together with a fuller understanding of the most appropriate design mechanisms, materials and approaches to laboratory and field testing, and to quality assurance. The results of this analysis, together with a parallel analysis of the alternative model in which the design and testing "intelligence" is devolved to the field level, will need to be incorporated into the cost model. Third, the initial flow chart for screening 3DP requests (Figure 2) will need to be modified in the light of developing knowledge and emerging/improving technology. The result of this analysis will also need to be integrated into the cost/benefit analysis.

A further aspect of this analysis will be to evaluate the optimal location for a printer as well as the factors that influence this decision. On the one hand, positioning a printer as far downstream as is practicable would maximise the logistic and postponement benefits described above. On the other hand, adopting such a strategy would lead to an increased burden in training and equipment purchases/maintenance. In short, at this stage it is unclear whether a strategy that positions the 3DPs at a suitable decoupling point such as the local distribution centre and is supported by a relatively small number of trained personnel but reduces the benefit of postponement, is to be preferred to one in which the printer is located as close to the beneficiaries as is practicable.

Importantly, future research must also be conducted in such a way that it takes into account the fast-developing capabilities of 3DP. For example, the cost of the bottom of the range machine from one of the main suppliers ("UP") has reduced from \$10,000 in 2010 to < \$700 in 2015, whilst the capability (speed and granularity) has increased over the same timeframe. A further consideration is that the production of items of WASH equipment as part of the trial described above was deliberately chosen as reflecting a low tech, but commonly used, range of spare parts. In this way, it was intended that an understanding of the limitations of the people, processes and technology triad would be developed from the bottom up. Clearly, however, there is potential to use different 3D techniques as well as machines that "print" with different base materials (e.g. metal). However, there is a danger that the hype surrounding the emergence of 3DP may lead to inappropriate uses – for example, the FDM system described in this paper has clear limitations in terms of, say, its safe working load or the pressure of a liquid that is contained within an item of pipework. Thus, it is strongly recommended that a *hasta lente* (make haste slowly) approach be adopted, and that new avenues for the use of 3DP be investigated using the methodology outlined above which will not only capture the financial costs/benefits, but also the softer areas around training and education.

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Note

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