3D Printing (3DP): A humanitarian logistic game changer?

Peter Tatham
Department of International Business and Asian Studies, Griffith Business School, Australia, p.tatham@griffith.edu.au
Jennifer Loy
Queensland College of Art, Gold Coast Campus, QLD 4222, Australia, j.loy@griffith.edu.au
Umberto Peretti
Department of Management and Engineering, University of Padova, Vincenza, Italy, peretti.umberto@gmail.com

Abstract
This conceptual paper discusses the benefits and challenges of using 3DP to support the logistic response to natural disasters/complex emergencies and in development activities. It concludes that 3DP has multiple advantages including speed (in comparison with conventional re-supply timelines) and the ability to use a single raw material from which multiple items can be created and/or customised to meet the particular operational circumstances. The paper recommends further research to provide a robust cost/benefit analysis and the undertaking of a field trial both to confirm the perceived benefits and to highlight alternative, as yet unforeseen, advantages and challenges.

Keywords: 3D printing, humanitarian logistics, logistic postponement

Topic: Humanitarian operations and crisis management

Methodology: Case Study

Introduction
The aftermath of a natural disaster or complex emergency requires those responding to set up a supply network in which the goods and services necessary to cater for the needs of the affected population are delivered as efficiently and effectively as possible. 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; Tatham *et al*, 2013).

Not least spurred on by the growth in numbers affected by disasters and emergencies (Guha-Sapir *et* al, 2013), humanitarian logisticians are actively searching for ways in which the efficiency and effectiveness of the supply network can be improved. One such emerging possibility is the use of three dimensional printing (3DP) technology which has the potential to manufacture a particular item of equipment (such as spare part) at a location that is close to the affected area. In doing so, it would avoid the delay inherent in obtaining the required item from a distant location (be this in country or abroad) as well as achieving an improved 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.

Aim

The aim of this conceptual paper is, therefore, to review the potential for using 3DP technology in support of the preparation and response to a natural disaster or complex emergency and to indicate areas of further research.

To achieve this aim, the paper will begin by outlining the currently available 3DP technology. This will be followed by a short section in which 3DP is positioned within the existing theoretical framework of logistic postponement. This will be followed an overview of the humanitarian logistic challenge together with the results of a recent review of the relevant literature. Thereafter, a case study of the potential use of 3DP to support the provision of water and sanitation (WATSAN) services will be discussed before the final section of the paper which will provide suggest the direction of future research.

An introduction to 3DP Printing technology

3D printing, technically known as additive manufacturing (and also known as rapid prototyping), refers to a range of technologies that build objects up in layers without the need for a mould or cutting tool. By doing so, it 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 (Cohen *et al.*, 2014).

The actual technology for the delivery of 3DP is fast developing, with multiple ways by which the process of additive manufacturing is met. These include:

- 3D printers which are basically the same as 2D printers and employ a row of print heads which make small deposits of material or binder (depending on the system).
- 'stereolithography' (SLA) machines which hold a vat of resin in which a platform is lowered incrementally whilst successive layers of the resin are cured by laser.
- 'selective laser sintering' (SLS) which fuses small particles of plastic, metal, ceramic or glass powders into a mass that has the desired three-dimensional shape. This is achieve by using a laser that selectively fuses the powdered material by scanning cross-sections generated from a 3-D digital description of the part onto the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the item is completed.
- 'fused deposition modelling' (FDM), in which the machines operate by heating a filament of material, usually a polymer, that is then extruded in a continuous feed whilst the bed of the machine moves slowly downwards thereby allowing an object to build.

In considering the potential benefits of 3D printing in a humanitarian logistics context where a 3D printing machine is to be physically situated at or near a relief site, machines utilising the fused deposition modelling (FDM) approach are proposed because they are:

- Portable – FDMs include the smallest of the 3D printers which start at desktop sized printers with a bed of around 125–150 mm cubed. By comparison, whilst the more sophisticated SLS machines may have a build platform as small as 200mm cubed, their physical size starts about the same as a public photo booth and then goes up to a size capable of printing a car. Furthermore, SLS machines require a stable manufacturing environment that includes, for example, nitrogen. SLA machines are also increasingly available in a size that is portable, but their design and operation is such that they are more appropriate for use in prototyping, as distinct from production. Neither SLA nor SLS machines will, therefore, be considered further at this time.
- Low capital investment – the lowest cost FDMs start at around $AU 1,600.
- Easy to operate – FDMs can, for example, be used outdoors if necessary (although wind strength and changes in humidity will affect them).
- Relatively low cost to run – the filament for a portable FDM is inexpensive, with 1kg of polymer costing $60-$125 depending on the grade of the material.
- Easiest to maintain – desktop sized FDMs are the easiest of the 3D printers to make adjustments to on site, and/or to repair if damaged in transit.

An example of one such portable FDM printer being demonstrated outdoors to the general public is a Figure 1.

Figure 1 - Photograph of a portable FDM printer
(Source: The Authors)

As indicated earlier, an FDM has a filament of material which is heated and extruded in a continuous feed whilst the bed of the machine moves slowly downwards, allowing an object to build. The 3D printer in Figure 1 has a single print head which can be used to build complex objects using an engineering grade polymer called acrylonitrile butadiene styrene (ABS). ABS is a thermoplastic which means it can be reshaped with heat – hence its suitability for fused deposition modelling. 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, but it is generally a strong, reliable material suitable and, hence, appropriate for the sorts of applications that will be described below.

Theoretical Framework

One of the key challenges within the overall field of supply network (or chain) management is that of responding to the ever increasing levels of volatility in demand (Christopher and Holweg, 2011). One frequently suggested approach is that of the use of ‘postponement’ techniques in which the inventory is held “in a generic or unfinished form, with final configuration being completed rapidly once real demand is known.” (Christopher, 2011, p. 102). It will be seen from the above description of 3DP that it enables just such a strategy to be adopted. The raw material (ABS) is held in generic form and then once the demand for a particular item or design of item has crystallised, it can be manufactured in a relatively short timeframe. Taking this theoretical lens one stage further, the point of manufacturer can be seen as representing the ‘decoupling point’. Prior to this point the raw material can be supplied using ‘lean’ techniques with forecasts of consumption being at a generic level, with the material itself being created and supplied in economic batch quantities. Beyond the decoupling point, an ‘agile’ approach can be adopted whereby production of the specific item is demand driven and locally configured (Christopher, 2011).

Humanitarian Logistics

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, accommodation, 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 or the 2013 Typhoon Haiyan in The Philippines) 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.

At one level, the HL challenge of matching demand with supply is somewhat easier than that facing a typical supermarket chain 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 non-food item (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 physical (e.g. road and bridges) and telecommunications infrastructure, multiple casualties, 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 have to be assessed by the responding agencies as those affected are primarily focussed on recovering from the disaster/emergency event.

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 (for example to the operation of water pumping equipment) are inevitable, and the resultant requirement for spare parts etc, in effect, creates a fresh, unforecast, demand. The use of 3DP technology is perceived to have a clear logistic benefit in a number of respects:

- Firstly, production of an item at or near the location in which it will be used has the potential to save significant time by obviating the need to order, and subsequently transport, the item from an external source.
- Secondly, the use of a single raw material 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 transport – for example through the movement of reels of ABS that require limited packaging and have a high mass to volume ratio, rather than finished goods. 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, 2014).
- Thirdly, for historic reasons, there may be incompatibilities between the equipment supplied by different aid agencies. For example, de Leeuw et al. (2010) outline the challenges and complexities in attempting meet the UN Water, Sanitation and Hygiene (WASH) Cluster’s aim of a global stockpile sourced from and funded by aid agencies. These authors note that equipment provided by one agency 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, use of 3DP would potentially be able to manufacture a suitable item of equipment that can overcome such challenges which are difficult to forecast (and hence pre-position the relevant items) in advance.

Review of the literature relating to 3DP in an HL context

Given the potential benefits of the 3DP in support of the HL challenge as outlined above, an analysis of the relevant literature was undertaken. This was firstly achieved through an inspection of the most recent reviews within the field which are to be found in Altay and Green (2006), Kovács and Spens (2007), Natarajathinam *et al*. (2009), Pettit and Beresford (2009), Overstreet *et al*. (2011), Caunhye *et al*. (2012), and Kunz and Reiner (2012), together with the informal bibliography of Tatham (2014).

As this initial review did not identify any academic research that specifically focussed on the use of 3DP in an HL context, a second review was undertaken 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 below:

Table 1- Results of the database search

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

An initial inspection of the results showed that 4 papers were duplicates and, notwithstanding the search string, a further 11 were not in any way relevant. These papers were, therefore discounted.

Upon inspection, it was clear that a significant number of publications were related to (a) the use of 3DP in a medical context – for example for the manufacture of prosthetic limbs (e.g. Thilmany, 2010), and (b) the design of communications systems. Whilst unquestionably of 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 8 papers were identified for further analysis, but after an inspection of the content of these it was clear that none discussed the potential use of 3DP in an HL context.

In summary, from a logistic perspective and in line with the theoretical framework of postponement and the use of a decoupling point outlined earlier, the employment of 3DP techniques has potential benefit:

- Through the local manufacture of items to meet an identified need thereby avoiding the inevitable procurement and transport delays.
- In avoiding the transport and warehousing of items to the affected area that are subsequently not required.
- By transporting the base commododity (ABS) that has a high mass:volume ratio and limited packaging requirements, and from which multiple components can be manufactured.
- In the production of bespoke items that are not normally part of the standard inventory in order to meet the specific operational requirements.

With these scenarios in mind, the next section will offer a case study in which 3DP might be used in a water and sanitation (WATSAN) context.

3DP Meets HL: A WATSAN Case Study

The general area of WATSAN offers a useful example of how the 3DP concept might be operationalised in a humanitarian context. Given that Oxfam is a world leader in this 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 (10 kits); storage (18 item/kits); distribution (13 items); and associated fittings (43 items), and in each case a ‘kit’ contains multiple components. As an example, the following is the entry for a right angle pipe connector.

Code G105	Elbow, Compression 90° 32mm
Definition:	Elbow, 90°, 32mm 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 or carton
Gross weight:	0.90kg
Volume:	0.0035m^3
Dimensions:	10 x 6 x 6cm

Figure 2 -Elbow Joint Specification from the Oxfam Catalogue (with kind permission of Oxfam GB)

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. It is estimated that printing this single end piece, complete with screw thread in ABS would take approximately 45 minutes on a small desktop, open filament printer. The resultant part could then be used immediately without any finishing procedures required.

It would also be technically possible to print the three separate parts (as in the original shown at Figure 2) with integral screw threads and using different materials – for example the central section being made from a rubber material. Whilst it is possible to print with a rubber like material such as thermoplastic polyeurethane (TPU) on some types of 3DP, this is not yet available for use on a small FDM machine such as is being considered for use here. However, 3D printing is not a straight forward substitute technology and, rather than making a direct copy, the part should be considered in relation to the constraints and opportunities and may therefore be completely redesigned to achieve the required purpose in a different way that is compatible with the use of 3DP. For example:

- The technology allows objects to be 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.
- Secondly, and most significantly, 3D printing 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 part shown in Figure 2 came to be fitted, there was a complication that meant the angle of bend should be 80 degree or 120 degrees, then a single new object could be 3D printed to exactly fit. 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.

It is conservatively estimated that the complete new part could be manufactured by a 3DP in some 2-3 hours which is likely to reflect a considerable advantage over the alternative of shipping the item into the affected area. Furthermore, both the 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), provide further advantage over the traditional logistic and manufacturing approaches. It is, of course accepted, that such an item might be able to be purchased locally, however this would still take a finite time to locate and transport.

Beyond the capabilities of the machine itself, a number of practical support aspects of the technology will need to be addressed in relation to the proposed Hl context for its use.

- The consistency of the power supply, for example, will need to be taken into account. This factor specifically points to the proposed use of the filament desktop FDM in that any interruption to the power supply will cause the print to fail but not compromise the machine itself (whereas larger FDMs can require 'powering down' so any interruption in power supply can cause problems). 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 for example, aftershocks, then an open filament 3D printer is the most suitable as the software includes a pause button, so the print head could be stopped mid-print until the event has past.
- The other support aspect of 3D printing is in relation to the 3D modelling software. Where the operator is simply replacing a damaged piece of equipment, the process would be straight forward. However, it may be a more complex issue 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, 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 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 the material and printed objects within which they could be used safely and reliably.

Based on these considerations, the use of 3D printing for the manufacture of water supply components would most effectively centre on providing agency field staff with the ability to alter a generic computer model set up with parametric capabilities to respond to problems identified during fitting or operations. The 3D printer could be used to create a part *ab initio*, to reprint a part that was broken in transit, or to print a modified part to fit an unusual or difficult site situation. In each case, the 3D computer models would be designed specifically for 3D printing to maximise the technology rather than merely replicating injection moulded parts.

It follows, therefore, that the provision of a 3D printing facility necessitate the development of a system that enabled the field worker to access and adapt parts on site, together with the subsequent design and testing of such adaptations. In this respect, it is clear 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 3D printing.

Summary and areas of further research

As indicated above, this conceptual review of the potential use of 3DP in an HL context has outlined a number of areas of potential benefit:

- In avoiding the transport and warehousing of items to the affected area that are subsequently not required.
- Through the local manufacture of items to meet an identified need thereby avoiding the inevitable procurement and transport delays.
- Through the use of a source material that does not require special packaging and/or handling, and has a high mass: volume ratio.
- In the production of bespoke items that are not normally part of the standard inventory (be this held locally or remotely).
- By introducing benefits (such as in line filtration) which cannot easily be created using mass production (injection moulding) techniques.

From a financial perspective, the initial capital cost is relatively small (<$2,000), as is the cost of the raw material. On the other hand, maximising the capability of a 3DP system would require investment in training and education of the field staff earmarked to use it, together with investment in the development and acquisition of the necessary parametric models and associated performance testing and standards compliance regimes.

The next stage of the research is to underpin this initial review with 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. Thereafter, it is proposed that a field trial, with an estimated duration of 6 months, be undertaken in an appropriate post-disaster or development situation. This should be overseen by an appropriately qualified team with the relevant technological and logistic skills, and carried out by an individual who has both the competence and knowledge to operate the 3D printer, but also the vision to be able to seize on unanticipated opportunities.

The research location should be selected in such a way that it incurs changes in temperature and humidity over the trial period as these have the potential to impact on the 3DP process. It may also be appropriate to commence the trial using a commercial off-the-shelf 3DP system but, by virtue of the trial, to understand the benefits and weaknesses of such a system. This could lead to the creation of a bespoke HL-focussed system that is more appropriate for the generic post-disaster and emergency context.

Bibliography

Altay, N., and Green, W.G. (2006), “OR/MS research in disaster operations management”, European Journal of Operational Research, Vol. 175, No. 1, pp. 475-493.

Caunhye, A.M., Nie, X., and Pokharel, S.S. (2012), “Optimization models in emergency logistics: A literature review”, *Socio-Economic Planning Sciences*, Vol. 46, No. 1, pp. 4-13.

Christopher, M.G., and Holweg, M. (2011), “ ‘Supply chain 2.0’: managing supply chains in the era of turbulence”, *International Journal of Physical Distribution and Logistics Management*, Vol. 41, Iss. 1, pp. 63-82.

Christopher. M.G. (2011), *Logistics & Supply Chain Management (Ed 4)*, Prentice Hall, Harlow, UK.

Cohen, D., Sargeant, M., and Somers, K. (2014), “3-D printing takes shape”, *McKinsey Quarterly*, Jan 2014, available at: http://www.mckinsey.com/insights/manufacturing/3-d_printing_takes_shape?cid=other-eml-nsl-mip-mck-oth-1402 (accessed 7 Feb 2014).

de Leeuw, S., Kopczak, L., and Blansjaar, M. (2010), “What really matters in locating shared humanitarian stockpiles: Evidence from the WASH Cluster”, *PRO-VE 2010*, pp. 166-172.

Ellickson, P.B. (2011), “The evolution of the supermarket industry: From A&P to Wal-Mart”, *University of Rochester*, available at: http://paulellickson.com/SMEvolution.pdf (accessed 17 Dec 2013).

Fernie, J., and Sparks, L. (2004), *Logistics and Retail Management*, Kogan Page, London, UK.

Guha-Sapir, D., Hoyois, P. and Below, R. (2013), “Annual Disaster Statistical Review 2012”, *Centre for Research on the Epidemiology of Disasters (CRED)*, available at: http://reliefweb.int/sites/reliefweb.int/files/resources/ADSR_2012.pdf (accessed 15 Oct 2013)

Kovács, G., and Spens, K.M. (2007), "Humanitarian logistics in disaster relief operations", *International Journal of Physical Distribution & Logistics Management*, Vol. 37, No. 2, pp. 99-114.

Kovács, G., and Tatham, P.H. (2009), "Responding to Disruptions in the Supply Network – From Dormant to Action", *Journal of Business Logistics*, Vol. 30, No. 2, pp. 215-229.

Kunz, N., and Reiner, G. (2012) "A meta-analysis of humanitarian logistics research", *Journal of Humanitarian Logistics and Supply Chain Management*, Vol. 2, Iss. 2, pp.116–147

Natarajarathinam, M., Capar, I., and Narayanan, A. (2009), "Managing supply chains in times of crisis: a review of literature and insights", *International Journal of Physical Distribution & Logistics Management*, Vol. 39, No. 7, pp. 535-573.

Overstreet, R.E., Hall, D., Hanna, J.B. and Rainer, R.K. (2011), "Research in humanitarian logistics", *Journal of Humanitarian Logistics and Supply Chain Management*, Vol. 1, No. 2, pp. 114-31.

Oxfam (2013), "Oxfam GB Catalogue", available at: http://www.oxfam.org.uk/equipment/catalogue/introduction (accessed 25 Jan 2014)

Pettit, S.J., and Beresford, A. (2009), "Critical success factors in the context of humanitarian aid supply chains", *International Journal of Physical Distribution & Logistics Management*, Vol. 39, No. 6, pp. 450-468.

Tatham, P.H., L'Hermitte, C., Spens, K.M., and Kovács, G. (2013), "Humanitarian Logistics: Development of an Improved Disaster Classification Framework", *Proceedings of the 11th ANZAM Operations, Supply Chain and Services Management Symposium*, Brisbane 20-21 June.

Tatham, P.H. (2014), "Bibliography on humanitarian logistics", *HUMLOG Institute*, available at: www.hanken.fi/public/en/humlogbibliography (accessed 7 Feb 2014).

Tatham, P.H. and Rietjens, S.J.H. (2014), "Integrated disaster relief logistics: a stepping stone towards viable civil-military networks?", *Disasters*, (accepted for publication).

Thilmany, J. (2010), "Rapid prototyping gains new roles in humanitarian causes", *Mechanical Engineering*, January, pp. 46-49.

Waller, M.A., and Fawcett, S.E. (2013), "Click Here for a Data Scientist: Big Data, Predictive Analytics, and Theory Development in the Era of a Maker Movement Supply Chain", *Journal of Business Logistics*, Vol. 34, No. 4, pp. 249-252.