Can 3D Printing address operations challenges in Disaster Management?

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Abstract

Disaster management entails activities for responding to and recovering from disruption to normal conditions. Disasters restrict the ability of operations managers, but technologies such as 3D printing have been proposed as a means of overcoming some of the restrictions. This research uses a state-of-the-art review of 3D printing technologies to determine the current and future potential to meet disaster management challenges. Specifically, one of the main categories of items listed in the Sphere Project handbook is considered. The analysis evaluates short, medium and long term feasibility and provides a research agenda for 3D printing and disaster management.

Keywords: 3D Printing, Disaster Management, Humanitarian Logistics

Introduction

Between 2005 to 2014 around 1.7 billion people were affected by disasters (UNISDR, 2017). Disaster management (DM) includes a set of activities undertaken to provide support for disaster victims. Its importance is increasingly recognised by operations and supply management scholars as recent disasters have shown the challenges that disasters pose for infrastructure and supply chains (See Holguín-Veras et al., 2014).

The chaotic situations caused by disasters are characterised by resource limitations (Kovács and Spens, 2009), damaged infrastructure (Kovács and Spens, 2009, Tatham and Spens, 2011, Van Wassenhove, 2006), limited communication (Tatham and Spens, 2011), and uncertainty of the situation and unpredictability of the demand (Kovács and Spens, 2009, Van Wassenhove, 2006). Under these circumstances, the delivery of products and services to affected areas can become very challenging for relief organisations, especially in situations with high dependence on resources from outside the affected region.

Technology has been identified as a potential solution to support disaster operations (Galindo and Batta, 2013). The capabilities of different technologies can be of tremendous help to face several of the challenges currently encountered. Boin et al. (2010) argue that more research about applications to support the participants in disaster relief activities is required.

Among the different technologies available, Tatham et al. (2015) identify the potential of 3D printing (3DP) for humanitarian logistics and test the ability of fused deposition modelling (FDM). This is the process used in desktop printers to create parts by melting plastic filament in successive layers. Savonen et al. (2018) propose a portable 3D printer that can be used in humanitarian crisis using fused filament fabrication (FFF), which is the non-trademark version of FDM. FDM is popular in educational and hobbyist environments due to its low cost and the availability of open source designs. Other technologies such as Stereolithography (SLA) and Selective Laser Sintering (SLS) are more commonly used in industrial settings, for prototyping and manufacturing (Bandyopadhyay et al., 2015; Durugbo and Beltagui, 2015). The purpose of this study is to consider the use of such technologies and identify applications for 3DP in humanitarian logistics. The paper considers the current challenges in DM and the current or future potential of 3DP to meet these challenges. From an Operations Management perspective, the contribution relates to the potential of 3DP to support operations in uncertain conditions with urgent demand and limited infrastructure. To achieve this aim, the paper is organised as follows; the following section provides a brief introduction to 3DP technologies and their applications. Afterwards, we elaborate on the dimensions of DM, which are used for the analysis of potential benefits of 3D printing presented next. The final section introduces the conclusions of the study and opportunities for future research.

3D printing technologies

The term 3DP refers to a range of *additive* manufacturing methods that build objects in layers of plastic, metal or other material, directly from digital design files (Petrovic et al., 2011; Mellor et al., 2014; Holmström and Partanen, 2014). This definition captures a broad spectrum of processes and technologies, most of which use light or heat to create physical objects, without the cost penalties traditionally associated with tooling and low volume production (Weller et al., 2015). These processes include the laser hardening of liquid polymer (Stereolithography, SLA), laser melting of metal powder (Selective Laser Sintering, SLS) and extrusion of molten plastic (Fused Deposition Modelling, FDM) into solid objects. However in most industries, the use of 3DP remains limited to activities such as prototyping or to high-value, niche products such as aerospace components. Meanwhile ongoing research investigates the wider applicability of 3DP technologies, for example to the construction of housing, using computer controlled devices to build layers of cement. Meanwhile headline grabbing developments such as bio-printing – in which cells are placed in a culture to “grow” living tissue, represent future processes (Barnatt, 2013). Such processes are far removed from, for example FDM processes performed by machines costing a few hundred euros. The common factor is the means of combining digital and physical design and production.

Advantages for SCM include enabling mass customisation through postponement as well as enabling decentralised production (Schniederjans, 2017). These advantages have been investigated in the context of spare parts supply chains, in which demand is uncertain and often urgent (Khajavi et al., 2014; Li et al., 2017). The findings of such investigations demonstrate that with current and future technologies, the supply chains for products such as military jets can be supported in a more responsive and costeffective manner. Demand profiles for products in disasters share similar characteristics of uncertainty and urgency. Therefore the ability of current and future 3DP technologies to address DM challenges requires investigation.

Disaster management background

DM represents activities designed to provide support to disaster victims and communities because of the impact of disaster phenomena. These activities are oriented towards the provision of products and services to affected areas to reduce death and suffering. Gupta et al. (2016) argue that a disaster scenario is described by three important parameters labelled as disaster domains. These parameters are administrative functions, type of disasters and time phases of disasters.

Type of disaster

The nature of the phenomenon affects DM because each type of disaster has different challenges. Therefore, different hazards require different planning, preparedness and response. Based on their cause, disasters can be divided in natural, man-made or hybrid disasters. Natural disasters are caused by natural phenomena, whereas man-made disasters result from human decisions. The combination of natural forces and human decisions lead to hybrid disasters, which are often associated with neglecting risk of human activities.

On top of the cause of the disaster, it is important to be mindful of the effect in the area and the speed of development of the event. Van Wassenhove (2006) introduced a classification combining origin (natural and man-made) and speed of development (sudden-onset and slow-onset). This combination have a significant effect in the type of response required. The cause of the disaster can provide valuable knowledge about potential challenges (Kovács and Spens, 2009) because it affects the priorities, type of activities and the kind of preparation allowed/required.

Time phases of disasters

DM priorities and activities shift through time. To understand this evolution, four major phases of comprehensive emergency management (i.e. mitigation, preparedness, response, and recovery) have been proposed. Each one of these phases pursues different goals and they often overlap.

Mitigation is the stage in which hazards are identified and assessed as basis for planning and implementing long term measures. Mitigation is very commonly addressed by governmental authorities using cutting-edge engineering techniques for construction; forecasting and risk assessment.

Preparedness aims to support communities to plan their reaction to disasters. This stage starts when there is an imminent threat endangering the region which requires a set of activities to reduce the potential damage of the disaster. Common preparedness activities are location of emergency facilities, stock pre-positioning, and preventive evacuation.

Response is the stage including all the activities just before, during and immediately after the disaster strikes. It involves a high level of urgency and uncertain and chaotic situations (Holguin-Veras et al., 2012). Common examples are relief distribution, reactive evacuation, casualty transportation, search and rescue, and inventory planning.

Given the importance of the first 72 hours after a disaster strikes, different improvement measures have been proposed. These range from pre-acquiring products from suppliers (Falasca and Zobel, 2011) to investing in the capabilities of the DM processes (Kunz et al., 2014). However, lead-time reduction is still a major challenge.

The recovery phase involves repairs, restoration of service and reconstruction of facilities after disaster has struck. The level of urgency is lower and conditions more stable than the response stage (Holguin-Veras et al., 2012). There are some papers related to allocation of displaced people, infrastructure assessment, reconstruction, and promoting resilience. During the resources and donations decrease, partly because of reduced media coverage. Thus, efficient approaches to enhance recovery that can rely in local resources are an important driver for successful recovery.

Administrative functions

These are single aspects (or topics) that are studied as part of the DM field (Gupta et al., 2016). Based on the focus on disaster response and recovery, the classification provided by the Sphere Project handbook is used in this research. Based on practice and experience from the field, the sphere project handbook compounds a set of relevant guidelines and standards for DM operations. The goal of the initiative is to assure the level of quality and accountability of the activities performed after a disaster strikes (Sphere_Project, 2011). The handbook introduces a set of principles, core standards and minimum standards, which are combined to identify the minimum requirements to maintain human life with dignity, which are a universal entitlement of rights, and can help achieve minimum assistance standards (Darcy, 2004). The handbook provides a minimum set of standards for four technical areas and one section cutting across all the technical chapters:

- Water supply, sanitation and hygiene promotion
- Food security and nutrition
- Shelter, settlement and non-food items
- Health action
- Core standards (these ones work in conjunction with all the technical chapters mentioned above)

The core standards represent a set of guidelines shared by all activities, which include the focus on people, coordination and collaboration, assessment of the context, design of response based on the situation, transparency with stakeholders, and management of aid workers (Sphere_Project, 2011). These processes have to be managed simultaneously with the four technical sectors.

This research is focusing on the technical standards because of the complex conditions for disaster response caused by damaged infrastructure (Kovács and Spens, 2009, Tatham and Spens, 2011), limitations of resources (Kovács and Spens, 2009) and unpredictability of the demand (Kovács and Spens, 2009, Van Wassenhove, 2006) that has been reported the field. Moreover, Galindo and Batta (2013) noticed that one of the most common assumptions made by articles focused on DM is the immediate availability of resources, which contradicts the situation found in reality. This article is introducing an analysis of the chapter shelter, settlement and non-food items, which includes the following components:

- Shelters. These facilities are essential to support disaster victims because they offer protection and the delivery of products and services. However, because of the uncertainty in DM, it is complicated and expensive to ensure enough facilities are ready to meet demand.
- Relief items. This category refers to non-food items that are required to provide appropriate living conditions to disaster victims during their stay in shelters and refuges. It includes a broad range of products for individual and/or collective use.
- Tools and fixings. This items are required to support living conditions in emergency facilities, products that are needed for repairs, and other items that can support other relief activities such as search and rescue. The purpose is to provide relief workers or citizens with the products needed to enable immediate response.
- Debris removal. During response and recovery it is important to re-activate infrastructure and communications through the removal of debris produced by the disaster. This category allows the production of spare parts for machinery dedicated to debris removal in the disaster area.
- Clothing. The type of disaster and duration of the emergency restrict the number of clothing items that victims can carry. The items included in this category are important to provide appropriate living conditions to the victims and they can rely on the availability of other items for cleaning and mending.
- Safe public building design and construction. This class of items includes parts that can be used to substitute or repair damaged sections, which becomes important in situations in which multiple disasters make repairs essential to reduce vulnerability after the first emergency.

Methods

Identifying the opportunities for 3DP to address DM challenges demands a multi-disciplinary perspective that captures the practical challenges and technological opportunities. Initially, a research of disaster response was used to understand the main challenges identified in the literature. The challenges were contrasted with Sphere project standards to determine potential areas for improvement. The technical chapter shelter, settlement and non-food items was selected for further analysis because of the potential support of 3D printing for producing these items. Afterwards, a state-of-the-art review of 3D printing technologies and applications was undertaken to identify the potential of current technology and the direction of future projects. The review centred on technical literature outlining the main categories of 3DP processes used in current practice (Barnatt, 2013; Bandyopadhyay et al., 2015). This was supplemented by identification of ongoing research projects in 3DP using resources such as the Wohlers report, which has provided annually updated data on the 3DP industry since the 1990s (Wohlers, 2016). Next, the results of the review in 3DP was compared to the standards of the Sphere project to evaluate the feasibility of current and future 3DP technologies to meet DM challenges. The sphere project standards were used as guidance to provide examples of the items required. The analysis was used to provide recommendations and elaborate on potential applications of 3DP technologies on DM.

Analysis

Using the requirements from the Sphere project, it is possible to understand some of the most relevant requirements for disaster response operations. Because of the nature of the different sectors and the potential benefits of 3D printing for production, we will focus on the group of shelter, settlement and non-food items. Looking through the standards in the branches of shelter and settlement, and non-food items, it is possible to see the potential of producing different components on-site. Based on that, the list of items presented in Table 1 was drawn. The table introduces the different category of items, the potential application of 3D printing technologies, the basic requirements for the use of these technologies, and the prospective timeline for feasible implementation.

Discussion & Opportunities

Analysis of the items required in DM contexts focused on evaluating the extent to which 3DP technologies could help. For each category, a judgement is made on whether the items could be produced with commercially available 3DP technologies in the short to long term. An assumption is made that cost is not a priority, since disaster response normally raises more pressing concerns. And it is assumed that technology development will continue along current trajectories, so that short term refers to the current time, while long term could be around 10-20 years away. We now discuss the findings in terms of the future potential of 3DP for DM and the opportunities for further analysis.

Short term

Temporary shelters and some relief items could be produced with currently available technologies at the time of writing. For both categories, however, some product design work is required to create designs that could be efficiently produced and assembled. Temporary shelters, for example, could be assembled from parts that would be designed for rapid production and to provide adequate shelter when connected. Whereas producing a usable shelter of adequate size in one piece is not feasible, designing components that are thin and can therefore be produced in larger numbers within the build envelope of a 3D printer, could be a promising means of creating usable products. Meanwhile for relief items, the aim would be to reduce the number of items that need to be shipped or stored. Cups and storage containers, for example could conceivably be 3D printed if required, meaning that essential, non-printable items such as food and medicines could be given priority in storage and transportation. If a truckload of supplies is sent a disaster hit area, it would be preferable to fill it with food rather than cups and 3DP could help. As the capabilities of 3D printers and the range of available materials increases, the potential of 3DP will grow.

Medium term

Although 3DP technologies have been commercially available since 1986, recent years have seen rapid growth. It took 20 years for the market to reach a size of $1bn, a further 5 years to reach $2bn (Wohlers, 2016). Forecasts for continued growth mean the scale of production and improvements in technology are expected to increase.

Table 1. Shelter and non-food products required for disaster response and recovery

Standard	Category	Description	Role of 3D printing	Requirements (in addition to 3DP equipment)	Feasibility
	Transitional shelter	Shelters that are temporary, relatively durable and flexible (i.e. reusable)	Ability to produce components designed to be connected/assembled into required shapes (e.g. Hexayurt[1])	* Designs that can be rapidly produced in small components for assembly * Plastic or metal materials	Short term. Using current technology, such as SLS
	Debris removal	Spare parts for machines damaged by the disaster and used for response activities	Ability to produce small components and spare parts	* Designs for required components, or ability to receive from producers. * Relevant materials, such as nylon powder or liquid polymer. * Machines for debris removal	Short – Medium term. Using current technology, such as SLA or SLS
S - Construction	Safe public building design and construction	Building or repairing facilities based on construction standards, with participation of the affected communities.	Production of sections and components for infrastructure repairs for multiple or ongoing disasters.	* Designs for required structures or ability to create and customise designs. * Relevant materials, such as metal, sand or cement according to technology	Medium-Long term: Relevant current experiments include Copenhagen's Building on Demand[2] and Amsterdam's MX3D bridge[3]
NF - Support items	Relief packages	Focused on the delivery of supporting items (i.e. cups, storage containers, sleeping bags, raincoats, squeegee)	Ability to produce small items for everyday usage.	* Designs for required items, ability to create designs or access to databases, e.g. thingiverse[4]. * Relevant materials such as plastic filament	Short term. Using current technology, such as FDM.
NF - Clothing and bedding	Clothing	The production of blankets, clothing and shoes.	Production of clothing products on demand.	* Designs for required items or ability to create designs * Relevant materials such as plastic powders	Medium-Long term. Current applications are largely fashion-oriented and may not be suitable for emergency use.
NF - Tools and fixings	Tool sets	The production of tools used for response and recovery activities (i.e. shovel, masks, gloves, chisels)	Ability to produce products or components with functional properties.	* Designs for required items or access to databases * Relevant materials	Short-Medium term. Current technologies such as SLA and SLS produce products, but materials may not offer sufficient functionality.

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[1] https://Hexayurt.comv

[2] https://3dprinthuset.dk/the-bod

[3] http://mx3d.com/projects/bridge/

[4] https://www.thingiverse.com/

For DM, this means the feasibility of producing items such as tools and spare parts, may change within 5-10 years. At present, many aspects of 3DP processes are not well defined, meaning the functional properties are not adequately controlled. For example, whereas centuries of use mean the chemical, thermodynamic and metallurgical characteristics of cast metals are well understood, the same is not true of 3DP processes. Moreover, for producing tools such as hammers or wrenches, 3DP is inefficient and produces inferior results. The advantage of 3DP for tools and fixings, however, comes when no other option is available. For example, astronauts on the international space station created a spanner labelled "made in space" by 3DP, which could not be produced by other means without waiting for supplies from Earth. Similarly, if a disaster means a group of individuals are cut off from outside help for a period of time, the ability to produce tools, however inefficiently, would be valued.

For debris removal, assuming the required equipment is present but damaged or in need of parts, 3DP could be very useful. Currently available technology may be adequate, for example some studies have looked at the current potential of 3DP in aerospace spare parts supply chains (e.g. Khajavi et al., 2014; Li et al., 2017). The stumbling block at present is likely to be the reluctance of producers to make available the design files for producing parts. Even when parts are produced by 3DP, producers seek control over their designs and may have concerns over liability when they do not control the quality of production. Only when such legal questions are resolved adequately will it be possible for 3DP to be used.

Long-term

Forecasting the capabilities of future technologies can mean entering the realms of science fiction. Noting current experimental uses of 3DP, however, it is foreseeable that clothing and construction could be feasible applications within 10-20 years. Current uses of 3DP are mostly in high-end fashion – spectacular shoes or dresses that are as impractical to create by traditional methods as they are unsuited to DM applications. At present, it seems farcical to propose using 3DP to make blankets or cold weather clothing, but as with relief items, the ability to create such items would allow storage and transportation to be devoted to food and medicine. Research into materials for practical as well as fashionable clothing may make 3DP viable for DM. For example, sportswear manufacturer Adidas, has recently begun producing customised shoes in stores. While these remain premium products with limited availability, increasing the scale of production may allow practical clothing to be produced in future.

Meanwhile, several research groups across the world continue to apply the computer control aspects of 3DP to construction. Two notable projects cited in Table 1 have involved building a metal bridge and an entire house by adapting the scope and expanding the scale of 3DP methods. Continued research in such areas would create the potential for 3DP to repair and build lasting structures, with profound impacts for DM.

Conclusions

This study set out to examine the feasibility of 3DP for overcoming DM challenges. Through a state-of-the-art review, the short, medium and long term possibilities have been outlined. There are, however considerable barriers even in the short term to fulfilling the potential of these technologies. Technological issues require ongoing investment, which may be more realistic as the market potential grows. Legal issues may prevent short term benefits, while human rather than technological is also required. Based on the findings of this study, we suggest three avenues for further research.

Understanding and overcoming time and cost constraints

Previous studies that used 3DP in humanitarian contexts (Tatham et al., 2015; Savonen et al., 2018) did so in contexts with cost but not time pressure. These studies focused on helping areas affected by poverty to overcome manufacturing capacity restrictions. Disasters differ from humanitarian crises in a number of ways, such as the duration and speed of onset. Thus far, there is no evidence of 3DP use in DM contexts. Future studies could investigate how the urgency of response and the functional properties of 3DP products interact to affect feasibility. This could, initially at least, follow studies in supply chain contexts that use simulation (Khajavi et al., 2014), including system dynamics models (Li et al., 2017).

Evaluating the skills requirements for 3DP

In a DM context, it is conceivable that all of the most advanced 3DP tools may be available, but not useful without the presence of skilled users. In particular, two areas should be a focus of attention in evaluating and improving the skills required for 3DP, namely design and operation. 3DP processes differ from other manufacturing methods, meaning that those trained to design products may need to update their knowledge and understanding (Petrovic et al., 2011). Indeed, as the processes develop rapidly, the design rules are not yet well established and therefore demand skilled designers to create designs that can be produced. Design libraries can be created, for example allowing tools or parts to be downloaded for printing. However, 3DP also demands skilled operators who are able to carry out the setup, printing, post-processing and maintenance activities required. A more complete assessment of the skills requirements should be a priority, in order to develop adequate training to make 3DP useful for DM and indeed operations in general.

Investment decisions and resource sharing

At present, investing in 3DP for the specific purpose of DM does not seem a wise use of resources. Assuming time constraints are not too pressing and assuming skilled engineers are available, 3DP can be useful, but it is difficult to justify resources kept solely for disaster preparedness. It could, on the other hand, be wise of local governments to invest in 3DP for other purposes, with the added benefit of assisting DM. One of the key benefits of 3DP in this regard is the relative ease with which resources can be shared (D’Aveni, 2015). Whereas most organisations would not make enough use of a 3D printer to justify investment, paying for access to shared devices would be beneficial. Design files can be transferred digitally and queued for production, meaning that several companies or individuals could share one or more printer. Private or public investment in shared 3DP resources would help entrepreneurs and businesses to create prototypes or enable small scale production, bringing economic benefits and ensuring resources that could be co-opted for DM. Research could investigate the benefits in areas where such investments have been made as well as identifying the impact on resilience in the event of disasters.

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