Additive Manufacturing, Supply Chains and Disaster Response

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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I. Introduction

One aspect of Additive Manufacturing (AM) technology, an automated layer-wise processing technique, that has been gaining attention is its potential application in remote areas or situations that feature significant supply chain disruptions (Meisel et al., 2016). This technology, that is used in the aerospace, automotive and biomedical fields, has also been discussed in the context of natural disaster relief efforts (Gregory et al., 2017; Guo & Leu, 2013; Meisel et al., 2016). This paper will focus on the later example, disaster relief. According to the United Nations International Strategy for Disaster Reduction (2009), the definition of a disaster is "a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources"(p. 9). These situations necessitate outside resources be sent to a region through the establishment of an often-temporary supply chain. The supply chains and resources sent through them are highly unique to the individual disaster event. This makes it difficult for aid and government organizations to quickly make accurate decisions about type and quantity of supplies, as well as how to transport them. This topic is becoming increasingly important as “the frequency of natural disasters has increased ten-fold since 1960…” (Institute for Economics & Peace, 2020, p. 49).

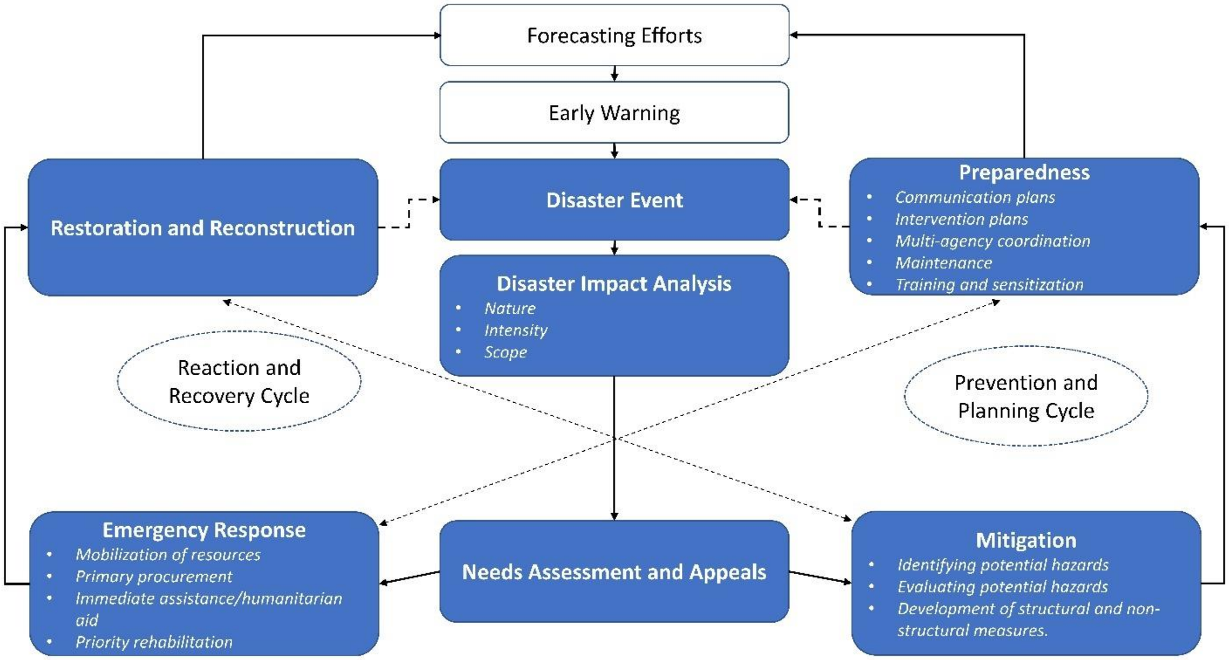
The logistics and coordination of resource distribution in disaster relief situations presents room for improvement. AM technology is one suggested technology to help improve responsiveness of aid to needs. In order to better visualize the effect of this technology, the STS portion of this project will study the disruptive nature of AM to supply chains and how it relates to a society’s ability to quickly and effectively respond to natural disasters. The paper will examine this topic through the lens of the Actor Network Theory and discuss how the introduction of additive manufacturing actors will alter the crisis response network. The technical portion of this project will examine the use of AM technology in the construction industry, by the design and fabrication of additively manufactured self-reinforced cementitious composites. More details on this topic and the connection between the technical project and the present STS paper are given in the technical report and sociotechnical synthesis, respectively.

II. Literature Review

In order to assess how AM fits into disaster relief (DR) operations, it is necessary to establish a reference model for a traditional (non-AM) DR supply chain. For the purposes of this study, the dual cycle model proposed by Maon et al. will be used, Figure 1. (Maon et al., 2009). This model examines DR networks in terms of two cycles, the reaction and recovery cycle, and the prevention and planning cycle. This model was selected due to its cyclic nature and it’s explicitly shown connections between the phases of response, that traditional linear models do not display. Furthermore, this model places a high degree of emphasis on the preparedness stage by including a separate cycle for prevention and planning, which is an important aspect to discuss when fully considering how AM can affect disaster relief.

Figure 1

Dual Cyclic Model for Disaster Relief Operations



Note: Figure is adapted from (Maon et al., 2009)

This model is just one example of a way to examine the complex and situationally unique character of traditional DR operations. Other studies have examined these concepts through the lens of Actor Network Theory (Porter, 2015; Weber et al., 2012). The Actor Network Theory (ANT) is a method originally developed by Michel Callon, Bruno Latour and John Law, which “represents technoscience as the creation of larger and stronger networks” with both human and non-human entities represented as actors in them (Sismondo, 2010, p. 81). This approach weighs technical, natural and social factors equally and views them in an interconnected fashion. This approach lends itself well to the analysis of DR networks, as these systems rely heavily on natural (the disaster), technological (supply chains and manufactured goods) and social (aid groups, governments and economic systems) actors. While other studies have used this approach for DR supply chains, none of the aforementioned studies consider AM in their analysis.

AM is a promising technology that has already been shown to have an impact on the ability of a country to respond to natural disasters, through its alteration of supply chains. One such alteration relevant to disaster response is the decentralization of manufacturing (Holmström et al., 2010; Petrick & Simpson, 2013). Attaran (2017) predicts that AM "could transform the global supply chain to a globally connected, but totally local supply chain" (p. 196). Decentralization or local manufacturing has already been proven to be beneficial in disaster relief efforts, by allowing for onsite manufacturing during a crisis. Several companies, including Oxfam, American Red Cross and Field Ready, are currently employing AM techniques for humanitarian aid (Saripalle et al., 2016). James (2017) has discussed in great detail the successful deployment of AM techniques by Field Ready in remote crisis situations by creating "3D designs for basic medical items so they can be 3D printed in the field" (p. 3). The onsite manufacturing and subsequent redesigns of supplies for medical procedures allowed for fast supply procurement time, whereas traditional supply chains could take over 4 months. While the onsite manufacturing of goods in difficult locations has shown promise, there are still several challenges that need to be addressed. One such challenge is apparent by the difficulty in selecting the correct materials and printers for a given application. To address this challenge, Meisel et al. (2016) details formal considerations that need to be addressed when selecting an appropriate AM technology class, equipment model, or material in remote areas. The most salient consideration categories were found to be "process, machine, part, material, environmental, and logistical constraints and objectives" (Meisel et al., 2016, p. 912). Each of these categories has numerous subcategories associated with them and present a spectrum of different considerations manufacturing faces in remote or disaster struck areas.

Additionally, AM allows for an increase in process flexibility when compared to traditional manufacturing. Muthukumarasamy et al. (2018) notes that “AM incorporates flexibility in the supply chain specially to meet and manage disruptions and disasters” (p. 517). Flexibility in the manufacturing process is a widely studied aspect of AM that has the potential to be instrumental in disaster response. Traditional means of manufacturing need large amounts of time to alter production runs, while AM technologies only require raw materials and a new design file. The potential of flexible manufacturing has been recently demonstrated by AM’s role in filling the holes in traditional supply chains and supplying medical equipment during the COVID-19 pandemic. During the pandemic, global supply chains were disrupted resulting in a shortage of ventilators and PPE (Ranney et al., 2020). Sinha et al. (2020) observes that the pandemic gave rise to an “informal PPE supply chain” that was made “feasible because of the rapid expansion of inexpensive additive manufacturing capabilities (3D printing) by small business and maker communities, wide availability of computer aided design software, and public design repositories” (p. 1162). The authors argue that the community should play a significant role in natural disaster relief and should be supported by governmental regulations. The study by Manero et al. (2020) expands on this idea, by identifying factors that are needed to coordinate an effective and rapid change of AM production lines to produce essential equipment. The roles of government regulations, coalitions with both physical and social networks, additive manufacturing of different products and file sharing are discussed.

The disruptive nature of AM to supply chains and how it relates to disaster scenarios is widely studied and the benefits and challenges are well documented. Furthermore, ANT is a concept used in numerous applications, including the analysis of traditional DR supply chains. However, to my knowledge, no ANT analysis has been performed on DR operation with the inclusion of AM technologies. The STS paper will build on the body of knowledge, by using the Actor Network Theory to identify relationships between actors and discuss how the incorporation of additive manufacturing technologies will alter the crisis response network. ANT is well suited to answer the posed question, because disaster relief can be easily visualized as a fast-acting network, in which each actor needs to exactly understand their role to ensure a timely response.

III. Methodology

In order to apply ANT in the STS report, current literature was leveraged to identify eight major actors in the disaster response network; the natural disaster, shipped manufactured goods, humanitarian aid groups, location, AM technology, available manufactured goods, infrastructure and affected community. Only natural disasters, such as earthquakes or tsunamis were considered for this work. Shipped manufactured goods refers to any finished products sent to affected areas to provide relief. Humanitarian aid groups were taken to be any private or governmental agency that is attempting to provide aid. Location refers to the geographical location of the affected area. AM technology is the machines, feedstock and skilled operators of the additive manufacturing machines. Available manufactured goods are the usable resources available to the affected community at given time during the DR operation. The affected community refers to the groups of people living at the location at the time of the disaster.

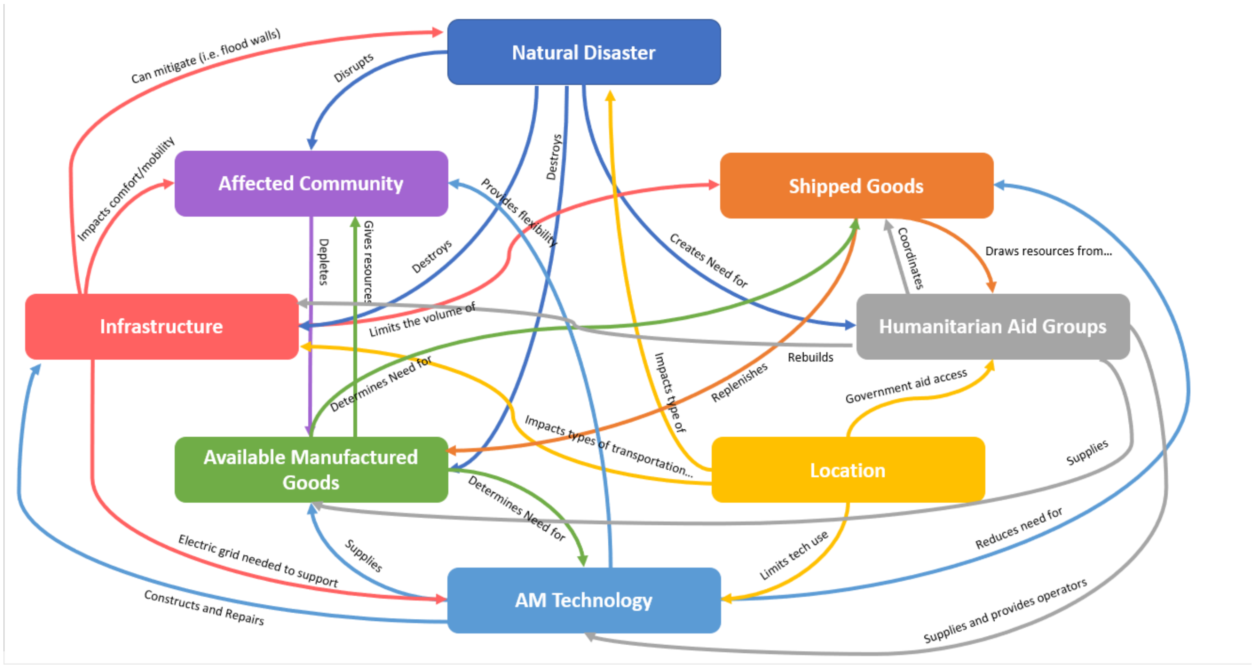
In order to assess the relationship between these actors, a systems diagram was constructed. This diagram is simplified due to the highly complex nature of these networks, but still provides a majority of the significant relationships between actors. Economical and governmental regulation actors, though important, were left out of this analysis, as they go beyond the scope of the work. In order to highlight AM contributions, the specific relationships of AM with other actors were examined during the reaction and recovery cycle of the DR operation cycles, as defined in figure 1. The potential impact of AM on the prevention and planning cycle will also be briefly discussed.

IV. Body

A simplified system diagram was created to show the connections between the eight salient actors identified in the methodology section and is shown in figure 2. As shown, all the actors have close relationships with each other and result in a complex system. The rest of the paper will focus specifically on the interactions of AM with other actors.

Figure 2

System Diagram Showing the Relationship between Actors in the DR Network



In order to implement an AM system in a disaster affected area, the machines, operator, software files and feedstock will need to be transported to the area in question. Thus, AM will have a relationship with infrastructure at the affected location. During the emergency response stage, the infrastructure at the site will need to be able to transport the technology into the area.

During events, such as earthquakes, this could pose a problem as the road and air transport systems may be impacted. Furthermore, as the machines themselves will require power to operate, the condition of the power grid of an affected area right after the event will need to be taken into consideration. Portable power sources may need to be brought with the machines. As the response proceeds into the restoration and reconstruction phase, the infrastructure will need to support a stream of feed material that is needed to fabricate the necessary supplies with AM. However, AM can assist in the reconstruction of the infrastructure through the use of concrete 3D printers. AM technologies have been identified as a possible method to construct housing shelters after a disaster that can be used during multiple stages of the relief process (Gregory et al., 2017). Similarly, the location of the event also acts upon the AM technology. Environmental factors, such as wind, heat, sand, salinity and humidity can affect the performance and operational life of the machine and the feedstock quality (Meisel et al., 2016). Thus, the location will dictate the effectiveness and type of AM processes that are appropriate for a certain response.

Additive technology has a very direct relationship with available resources and the shipped goods. By allowing for the automated fabrication of parts onsite, this technology is able to add to the supply of available resources. It also reduces the volume of manufactured resources that need to be sent to the site. While AM reduces the amount of ready-to-use essential materials that need to be shipped to a disaster site, the feed material for most of these machines still needs to be transported. Furthermore, the decentralized and small batch manufacturing of AM allows for a large amount of flexibility product design. If a certain design or specification does not fit the application or the situation evolves to have new needs, AM can easily change the fabricated resource to accommodate this. These aspects can give the supply chain in both the emergency response and reconstruction phases a more flexible nature.

The ultimate goal of the DR network is to help the affected community, through the help of aid groups. The implementation of this new technology will affect both of these actors. During the emergency response phase, the aid groups will act upon the AM technology by securing the funding for these machines and sending trained operators to the affected areas to run them. The AM machines will then form a relationship with the affected community, by providing them with resources with shorter lead times and taking into account feedback on needs and designs. Moving forward in the reconstruction phase, members of the affected communities could be trained to operate and maintain the machines for future use.

After examining the relationships of the AM actor with others in the network during the reaction and recovery cycle, the implications for the prevention and planning cycle can be theorized. The difficulty in planning for DR responses lies partially in the fact that all the natural disaster events are unique and require different supplies. They all pose new challenges in terms of destruction of infrastructure. Since there is an urgent need for a quick response, it can be difficult for aid groups to know what resources need to be sent. If worked into the preparedness phase of the prevention cycle, AM can provide a more generalized supply option to send into an area as a part of the emergency response. The type of materials and printing process would still need to be selected based on the specific event, but decision support tools are being developed to aid in the selection of AM machines and materials for use in remote environments (Meisel et al., 2016).

While this technology has largely positive effects on the ability of humanitarian aid groups to respond to a natural disaster, there still exist challenges and relationships not fully examined by this work. Firstly, the impacts of governmental regulation, technological limitations and economic considerations were not discussed. Government regulation and related logistics depend on the country the disaster occurred in, as well as the origin of the aid organization responding. Furthermore, the technology's needs, limitations and costs are dependent on the type of material and process used. For example, an extrusion-based concrete printer will have different demands and limitations than a selective laser melting metallic printer. The inherent complexities in these topics require a separate and more detailed analysis, whereas this STS paper was intended to study the merits of the technology more generally. Furthermore, there will need to be skilled operators with specialized knowledge hired to go to the affected areas and run the AM machines. This will require the introduction of a new training and recruitment program to humanitarian aid groups. This paper provides a good first step in examining AM in a DR network, but factors beyond the scope of this study need to be studied in order to more completely assess the feasibility of this actor's inclusion within the network.

Conclusions and Future Work

The implementation of AM within the disaster relief network has clear effects on the available supplies, infrastructure, affected community and shipped supplies, while needing support from the humanitarian aid groups. AM provides many benefits, such as flexibility of design, onsite manufacturing and quick changes in product manufacturing. However, there still exist challenges, like getting a fully powered machine onto the site, maintaining the supply of feed material and providing skilled operators. Future work may need to be conducted on the interactions between local and global governmental regulations and how this may affect AM in this application. Additionally, an economic analysis on the relative cost of AM over other forms of relief would provide useful information. Furthermore, the technical project supports this STS paper, by exploring the feasibility of producing self-reinforcing cementitious composites by additive manufacturing methods. If these composites are perfected, they could be used to print structures in remote and DR scenarios with significant tensile strength without the need for rebar. This STS study can provide the first step in helping current actors, such as companies, communities and governments, understand the implications of deploying AM in their disaster response plans.

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