3D Printing and Disaster Shelter Costs

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Abstract--**Natural disasters cause significant disruption to the lives of those affected by them. One of the major effects of natural disasters is the loss of housing. Additive manufacturing is a relatively new manufacturing technology that has advantages over traditional manufacturing. For example, AM facilitates rapid prototyping and offers cost advantages for lower volume production. In this paper, the potential of additive manufacturing for providing shelters after a natural disaster is evaluated. The costs of providing shelters to victims of natural disasters is compared with traditional shelter options. It is found that the cost of 3D printed structures falls within the range of traditional shelter options. With continuing improvements in additive manufacturing technology as well as in terms of materials used, additive manufacturing may become an increasingly competitive option for disaster housing.**

I. INTRODUCTION

The world is facing the impact of natural disasters on human lives and economy in both predictable and unpredictable ways on a large scale [19]. In 2008, 321 disasters killed 235,816 people, affected 211 million others and cost a total of US $181 billion [19]. A natural disaster can be defined as some rapid, instantaneous or profound impact of the natural environment upon socio economic systems [3]. The term 'natural disaster' is frequently used to describe rapid onset events that are triggered with the presence of natural hazards in the environment [25]. Hydro-meteorological and geophysical events ranging from floods, storms, and bushfire, to landslides, earthquakes, and tsunamis can cause injury, death and damage to property depending on the vulnerability and exposure to risks [25]. Natural disasters cause humanitarian, ecological, and economic impacts. *Humanitarian effects* include loss of life and the psychological effects to people after disasters; *ecological effects* comprise the loss of arable land, forests, and harm to the ecosystems [30]. *Economic effects* due to natural disaster are usually grouped in three categories:

- Direct losses: describe the physical impacts on infrastructure (transport, energy, and water), buildings, machinery, and agricultural assets. These can be caused by the disaster itself or via the following physical destruction [30].
- Indirect losses: occur as a consequence of the physical destruction of firms and households, e.g. business interruption and wages lost [30].
- Macroeconomic impacts: comprise the aggregate impacts on economic variables like the gross economic product (GDP), consumption and inflation due to the effects of disasters, as well as due to the reallocation of the government resources to relief and reconstruction effort [30].

Additive manufacturing, also known as 3D printing (3DP), is a technology that allows products to be created by adding layers of material to a substrate to form a three-dimensional object. In contrast to traditional manufacturing processes such as injection molding or machining, 3DP does not begin with a form or an existing material, but rather utilizes a computer model to guide the printing of the object [40]. This 3DP technology can make a significant difference to emerging response in developing countries by printing needed materials such as basic tools rather than transporting them from other countries. In addition, it could help the world's most vulnerable and the victims of catastrophes to rebuild their lives. 3D printing, a relatively new technology, may have an impact on some aspects of disaster management. The purpose of this paper is to evaluate the role 3D printing might play in disaster management costs.

II. LITERATURE REVIEW

The literature review is divided into three sections; a general overview of various aspects of disaster management (A), current theories and methods for disaster shelter/housing (B), which will be the main focus of our research, and current 3D printed housing technology (C).

A. Disaster Management Overview

Major natural disasters such as hurricanes, earthquakes, or floods create many issues both immediately after the disaster and during the reconstruction period. The cost associated with recovery from a natural disaster can include human resources, waste management, logistics, maintaining communication networks, and shelter for victims [5, 8, 22, 27, 28]. Disaster management, as defined by Ahmad [2], is "undertaking certain actions and coordinating activities so as to take safeguards and if it occurs . . . to restore the system's functioning which was disrupted due to sudden devastation and damage" (pg. 65). Thus, disaster management is the preparation and readiness for any kind of disaster that may occur. It also encompasses the plans for rebuilding in the aftermath of the disaster.

Coppola [11] describes four major components to disaster management. First, mitigation involves steps taken to prevent disasters from happening or to lessen the damaging consequences. Next, preparedness involves putting into place system of dealing with a potential future disaster. Third, response is the reactionary management to a disaster. Finally, recovery is the return to normalcy, a phase that can last for years after a major disaster. Review of the literature provided insight into some of the major issues encountered after a disaster. Current theories surrounding coordination and human resources, logistics, waste management, communication networks, and shelter/housing are presented, as shown in Figure 1.

1) Coordination and Human Resources

Some of the issues involved with disaster management include coordination between various agencies, logistics, and human resources [22]. Coordination is defined as "compatible and aligned strategies and actions of various departments or organisations which enable them to meet a shared objective" [22: pg. 92]. During the immediate emergency phase and into the recovery phase of a natural disaster, many organizations and agencies must work together. Maintaining reasonable coordination between these various, sometimes opposing groups, can lead to complications in disaster management. Regarding human resources, Idris and Soh [22, pg. 92] state, "successful handling of disasters requires the contribution of various parties that have the relevant skills and capabilities in areas such as distribution, engineering, health, security, et cetera. Costs associated with personnel include training, pre- and post-deployment briefings, and in-field facilities [22].

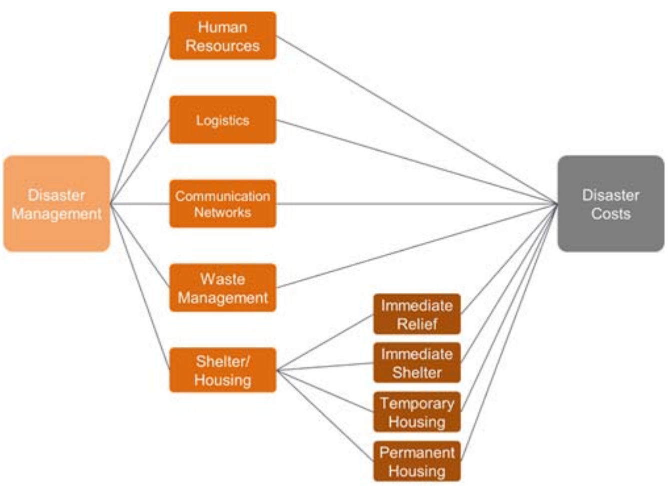

Figure 1: Disaster Management Cost Factors
Source based on [5,8,22,27,28].

2) Logistics

Thomas and Mizushima [36, pg. 60] define logistics 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 point of origin to point of consumption for the purpose of meeting the end beneficiary's requirements.". The main logistical issue involved with disaster management is the sudden dramatic increase in demand for a product or service and how the products will reach the site of the disaster [22]. In a disaster situation, "...the imperative is to procure and move the required materiel (water, food, shelter, clothing, medicines, etc.) from point A to point B in the most efficient and effective way possible" [8, pg. 2]. "Given that the overall annual expenditure of such agencies is of the order of US $20 billion, the resultant logistic spend of some US $15 billion provides a huge potential area for improvement, and consequential benefit to those affected by such disasters" [8, pg. 2].

3) Waste Management

One of the major issues of concern after a large disaster is that of waste management [28]. Earthquakes, hurricanes, floods, and tsunamis all have the potential to create huge amounts of destruction. Waste in the form of concrete, bricks, metal, and other materials must be removed from the disaster area. Karunasena, et al. [28] identify some of the current strategies used for dealing with the debris created from a major disaster. Some of the waste, such as bricks or steel, can be salvaged and reused in the post-disaster reconstruction. Other waste can be recycled, or even composted. Waste that is not reused or recycled is incinerated or placed in landfills, with careful consideration to identify any environmentally toxic materials. Waste is also generated during the reconstruction phase after a disaster, however this waste is usually more easily able to be recycled [28]. While these are the ideal standards for post-disaster waste management, not all countries have the resources to deal with waste appropriately. "One major problem is the non-availability of landfills for such a huge volume of debris left over by a massive destruction" [28, pg 181].

4) Communication Networks

Communication networks have been identified as a major issue in emergency management and information systems frequently break down during a major disaster [5]. Communication systems are critical to dealing with and recovering from a disaster event. Banipal [5, pg. 485] notes three major functions of communications after a disaster to be "search and rescue", "maintaining law and order", and "estimating loss." The technologies currently used for communications among rescue personnel involve reliance upon a central dispatcher. Different agencies have communication equipment that operate on different frequencies from each other. Current theories to improve communication during a disaster event include providing emergency personnel with the same radios, building a unified system that is shared among all agencies, utilizing a common frequency for communication, and implementing software-defined radio systems that do not rely on a central network to get messages to the disaster command center. Maintaining Wi-Max networks within critical areas of a city could provide internet access during a disaster [5].

5) Shelter and Housing

According to Johnson, Lizarralde, and Davidson [27, pg. 367], "Housing represents the greatest material loss; in earthquakes, houses collapse, floods sweep them away, and in lava flows they are smothered—always leaving behind families who are bereaved and in immediate need of shelter relief." In many developing countries, no formal plans are in place to help these families rebuild their homes. They are often left to make a temporary shelter with whatever materials they can scavenge or have at hand [27]. Adding to this, when it comes to rebuilding after a major disaster, the normally available local supplies and resources may not be readily available. Chang, et al. [7] point out that local resources such as production facilities are likely to have also been damaged in the disaster event. Comerio [9] had similar conclusions, stating: "Recent urban disasters have made it clear that housing is the single greatest component of all losses in terms of economic value and in terms of buildings damaged. As a result, the potential for a major housing crisis exists if there is no mechanism to provide alternative housing for victims or if there is no capacity to finance the repair or re-construction of units lost *in a reasonable time frame* [emphasis added]" [9, pg. 176].

B. Current disaster housing/shelter theories and methods

In 2005, Hurricane Katrina damaged or destroyed around 300,000 houses and displaced over 1 million people from their homes [17]. "As of November 2010, [Disaster Housing Assistance Program] Katrina had provided housing to 36,818 households at a cost of $552.8 million, and [Disaster Housing Assistance Program] Ike had provided housing to 25,316 households at a cost of $281.3 million" [13, pg. 3]. According to Johnson, et al. [27] and Quarantelli, [32], housing during the recovery stage of a natural disaster has four stages, as shown in Figure 2.

Johnson, et al. [27] state that, whatever the type of temporary housing used, it has to be:

- Organized — which departments will be responsible and mobilized?
- Procured — how will the housing be purchased?
- Delivered — which locations will be chosen and prepared?
- Set up — who has the responsibility for construction of the housing?
- Connected — to water, sewage, etc.
- Used — by victims appropriately selected
- Taken down — what happens to the residents at this time?

Development and distribution of any type of disaster shelter or housing must keep the previous requirements in mind. If individuals are unable to return to their homes after a disaster, they require what the Federal Emergency Management Agency [17, pg. 50] refers to as interim housing. "Providing the actual structures to house disaster victims during this interim period is the most tangible challenge that government officials face."

C. Current 3D Printed Housing Technology

Printed building refers to technology that uses 3D printing as a way to construct structures [18]. Forlee [18] has noted that the advantages of this technology include quicker construction, lower labor costs and less waste produced. Cost effective, environmentally sustainable, and affordable housing could be built using this technology. For example, a Chinese company, WinSun has recently built ten demonstration houses in twenty-four hours with large 3D printers using a mixture of quick drying cement and recycled raw materials. The cost of each house was $5,000 [18]. Crowe [12] has also noted that if the technology continues to develop and remain affordable, this type of application may quickly become an easy solution to address lack of substantial housing in developing countries and as temporary housing in disaster recovery.

At many universities around the world, work is going on to develop technologies capable of producing entire houses. One of the work is that of Behrockh Khoshnevis, professor from the University of Southern California. He has developed a technology called contour crafting [10]. This technology extrudes a stream of concrete and uses this extrusion process to print the walls of the house [21]. "The entire system sits on a large mobile gantry system that could be installed on rails at the construction site and be used to print the walls of the house, while other robots install lintels, electrics, and plumbing as well as the other components of the house, such as insulation and reinforcing" [21]. This 3D printer is capable of building a 2,500 square-foot house within 24 hours [12]. Likewise, Loughborough University and the Polytechnic Institute of Leira are also doing work in 3D printing for architectural purposes.

An example of continuous development is the method of production for 3D printing. For example the WinSun company does not fabricate its products in one, single print but instead they are printed in parts, moved to a construction site by conventional transport and are then put together by using conventional construction equipment and techniques [39]. Contour Crafting on the other hand, is working on a printer that can be moved to a construction site and then print a building at that location [29]. The Zhuoda Group fit in between these two as it prints complete modules, e.g. a kitchen, which are then combined on site.

Figure 2: Disaster Housing, adapted from [27,32]

3D printed buildings are constructed by Dutch and Chinese demonstration projects to foster greater innovation in 3D printing of residential buildings, and to educate the public to the possibilities of the new plant-based building technology [18]. According to Elissa Jun (FEMA), "As 3D printing becomes more developed and practical, it may allow for efficient and affordable production of housing for disaster recovery" [12].

III. RESEARCH QUESTION

Reviewing the issues and current strategies used for disaster management led us to the following research question:

How does the cost of using 3D printing technology to build temporary housing structures after a disaster compare with costs of current strategies for building temporary housing structures?

IV. CONCEPTUAL MODEL

Our research question is represented by our conceptual model within the greater framework of disaster management costs, as shown in Figure 3. That is, how do the costs of traditional shelters compare to 3D printed shelters?

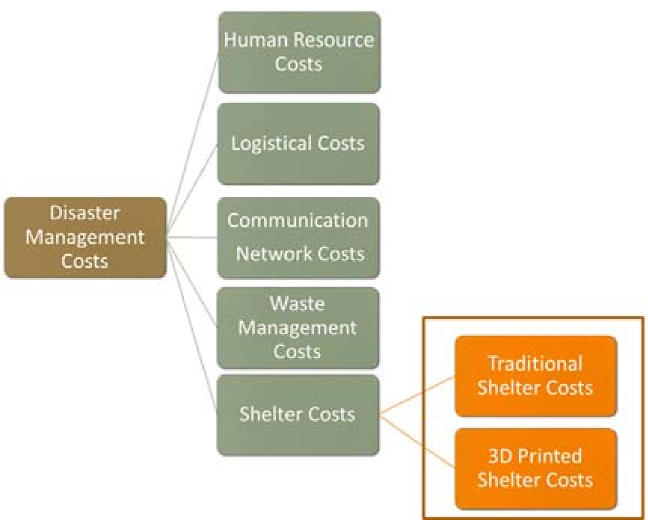

Figure 3: Conceptual Model

V. METHODOLOGY AND DATA COLLECTION

To begin gathering data about disaster shelter costs we first had to define traditional versus 3D printed shelters. We found traditional shelters to include several types. These included bamboo, timber frame, and steel frame. We also found complete prefabricated structure units including the Better Shelter (BetterShelter.org), the Exo housing system from Reaction, and Epoch Homes modular designs. Finally, we researched 3D printed shelters. Though 3D printed houses can be made of various materials, our research focused on extruded concrete shelters.

We utilized two methods to obtain information. The first method was to collect primary data by interviewing organizations and companies involved in providing or producing temporary shelters. We used open interview questions so we could gather insight into costs. Since there is limited secondary data, we chose this method to get appropriate primary data that was relevant to our research. We interviewed representatives of humanitarian aid organizations and representatives of companies producing temporary shelters. The second method was to collect secondary data on the cost of disaster shelters and 3D printed structures. Though our original goal was to use strictly primary data, due to the limitations discussed below, we used the limited secondary data that was available. This secondary data was able to provide data about various structures, as well as costing and material information. Our secondary data came from academic journals and company or organization websites.

We directly collected information pertaining to the cost of providing a shelter from companies and agencies involved in providing the shelters after a disaster. We ascertained the projected cost of providing 3D printed shelters to disaster areas. We identified two organizations currently involved in printing buildings using 3DP technology, WinSun and Contour Crafting. We initiated contact with members from each of these two organizations to ascertain the cost of 3D printing an adequate structure for post-disaster situations. We also asked about the ability to mobilize an appropriate 3D printer to a disaster area and the potential cost involved, and what materials would need to be procured. Overall, we collected information from several interviews with representatives of 3D printing companies as well as disaster relief organizations, as well as academic journals and organizational and company websites.

VI. FINDINGS

There are three types of disaster shelters/housing that we identified through our research. These are traditional shelters (A), prefabricated shelters (B), and 3D printed shelters (C). The International Federation of Red Cross and Red Crescent Societies published a comparison of eight different transitional shelters used to help victims of natural disasters [23]. The study identified the approximate material cost per shelter, the project cost per shelter, the number of people required to build the structure, the time to build the structure and the anticipated lifespan. In addition, the study also provided a performance summary as well as a risk analysis to determine the susceptibility of the structure to flood, earthquake and wind.

A. Traditional Shelters

1) Bamboo Shelters

Bamboo frame shelters were erected to provide temporary shelters after an earthquake devastated parts of West Java, Indonesia in 2009 [37]. The 6m x 4m shelter was made with local materials, which consisted of bamboo framing for the supports and bamboo matting and laths for the roof. The structure takes three to four people approximately a week to build two structures. The material cost per shelter was CHF 260 and the project cost was CHF 330. The shelter is designed to last 1-5 years and is highly susceptible to damage from earthquakes and moderately susceptible to flood and wind damage [37].

Refugees created as part of the conflict in Afghanistan were housed with a bamboo-framed structure. The 9m x 4.3m shelter is designed to act as a shell to protect individuals who are living in tents from the elements. Each structure is created with imported bamboo poles and plastic sheet walls and roof. The shelter is designed to last one year and costs 270 CHF for materials and 820 CHF for the project. It takes a team of seven people a total of three days to construct the shelter. The bamboo structures perform well in the case of an earthquake, but they are at risk to wind storms and floods [24].

2) Timber Frame Shelters

Timber frame shelters were built to provide housing after an earthquake hit Sumatra, Padang, Indonesia in 2009 [37]. The 4.5m x 4m shelter was made with local materials, which included timber framing, palm fiber roofing and walls, and a concrete bucket foundation. The structure takes approximately 2 days for a team of five people to build. The material cost per shelter was CHF 350 and the project cost was CHF 500. The shelter is designed to last 6 to 12 months and is susceptible to flood, earthquake and wind damage [37].

After a major flood ravaged Khyber Pakhtunkhwa and Gilgit-Baltistan Pakistan, timber frame structures were provided to offer temporary housing [34]. The 4.3m x 5.7m shelter was constructed with a low brick wall roughly three feet high to protect against further flooding and to keep in warmth. Seven triangular frames connected by a ridgepole provided the structure with support while the roof was made with corrugated steel sheeting. The structures can be built in one day by a team of four people. The material cost per shelter is CHF 500. The anticipated lifespan is 24 months. The shelter is very susceptible to wind and moderately susceptible to flood and earthquake damage [37].

Two different timber frame shelters were also used to provide disaster relief in Peru after a major earthquake in 2007 [37]. The Bolayna timber frame structures take a team of four people, which include an engineer and project manager a total of one day to build. The 3m x 6m structures are made with a Bolayna timber braced frame, a concrete slab floor, tongue and groove timber walls and a cement fiber roof. The approximate project cost of the shelter is CHF 560, while the material costs are unknown. While the house is expected to last a minimum of 24 months, it is easily damaged by floods and windstorms [37].

The Eucalyptus frame structures used in the Ica Province consisted of Eucalyptus wood poles, bamboo matting for the walls and plastic sheeting for roofing material. The structure takes a team of four people two days to build. The 3m x 6m building uses local materials (except the sheeting) and has a material cost of CHF 225. The cost to the program is an additional CHF 340. The structure has an expected lifespan of at least 12 months, but is highly susceptible to wind and flood damage as well as being moderately susceptible to earthquakes [37].

Wood framed shelters were used in the 2010 Haiti earthquake as well. The structures were built with a timber frame and gable roof. The walls are made with wood studs and plywood siding. The 21 square meter shelters cost 1,560 CHF for materials and 2,300 CHF for project costs. The shelter lasts 3-5 years and takes a crew of nine members 2-3 days to construct. The shelter is handles earthquakes and floods well, but has a moderate risk of wind damage [24].

A similar structure in Haiti named the “T-Structure” is designed to last much longer, five to ten years. The structure is built with metal roofing and has a covered porch. The walls are made with wood studs and plywood sheathing. The floor is raised and constructed with plywood. The structure is typically pre-manufactured and then shipped to the disaster area. The material cost of the shelter is 2580 CHF and the project cost is 5430 CHF. The structure takes a team of 5 to 7 people 3 to 5 days to build. The structure resists earthquakes and floods, but has a moderate chance of being damaged by high winds [24].

Another timber-framed shelter was used as a transitional shelter in the Philippines after a typhoon in December of 2011. The materials are found locally and cost 500 CHF. The 4.8m x 3.7m shelter consists of concrete footings, coconut wood for framing, plywood floors and walls and a corrugated iron roof. The structures take a team of five people a total of five days to build. The lifespan is 5 years with an approximate material costs are 500 CHF. The structure is moderately susceptible to wind damage, but handles earthquakes and floods well [24].

A larger more permanent structure designed to last 5 years was also used in the Philippines. It was built with concrete masonry half walls with coconut wood framing and plywood walls on the upper half. The roof was built with metal siding. The 4.0m x 5.0m shelter takes 12 days to build and costs 1,550 CHF for materials. The project cost for the shelter is approximately 2,000 CHF. This structure has the potential to be very durable; however, the durability is dependent on the proper connections between the components. The structure is at moderate risks to earthquakes and floods and has a high risk to wind damage because of the large overhangs in roofing design [24].

3) Steel Frame Shelters

After a major earthquake devastated much of Haiti in 2010, steel frame shelters imported from Spain were used to provide temporary housing relief [17]. The 3m x 6m structures took two days to build and consisted of a galvanized rectangular steel frame with a corrugated steel sheeting roof. The material cost of the structure is CHF 1700 and the approximate cost to the program is CHF 4300. The structures are expected to last 24 months, but easily damaged by windstorms and earthquakes. The structure resists damage from flood fairly well [37].

Steel frame buildings were also used in Aceh, Indonesia after the 2004 Tsunami [37]. It took a team of four or five people a total of three days to erect and clad the shelter. The structure kit consists of an imported steel frame and metal sheeting roof with local timber planks used to build the walls. The material costs are CHF 4765 (2004) and the project cost per shelter is CHF 5100. The shelter is highly susceptible to wind damage, but resists flood damage rather well due to the raised floor. The structures are designed to last a minimum of 5 years [37].

Steel frame buildings have been used as temporary housing shelters in Vietnam since 1997 [37].The shelter is made with a lightweight steel frame and plywood walls. The roof consists of corrugated sheeting and a concrete slab for the floor. The structures take six people a total of three days to build. The material cost of the shelter are unknown, but the project cost of the shelter is CHF 1500. The structure has an anticipated lifespan of 5 years and withstands flooding well. The structure is at high risk from wind damage [37].

4) Better Shelter (BetterShelter.org)

Better Shelter is a company located in Sweden. In a partnership with the IKEA Foundation and the UN Refugee Agency, they have created a product called the Better Shelter [6]. This freestanding structure consists of a frame, roof, wall panels, door, windows, floor, and even a solar panel. The total shelter unit packs into two boxes for shipping. A Better Shelter can be assembled in 4 to 8 hours and has a 3-year life expectancy. The cost of a Better Shelter is USD 1,150 [35].

B. Prefabricated Shelters

Prefabricated shelters are shelters that are readily built. For example, after Hurricane Katrina the U.S. Department of Homeland Security's Federal Emergency Management Agency (FEMA) supplied trailers and supplied them to the victims of the disaster for an affordable cost [16]. FEMA spent $2.7 billion on 145,000 trailers and mobile homes [38] thus with an average cost of $18,620 per unit. Similarly, after super storm Sandy, FEMA, trailers were used in New York [31]. Cost of these types of prefabricated shelters is higher than that of traditional shelters but the advantage is that they can provide longer term solutions. For instance, although the trailers were supposed to house residents for a maximum of eighteen months, five years after Katrina, 860 Louisiana and 176 Mississippi families still live in FEMA-owned shelters. Additionally, according to experts, thousands of other Katrina victims live in trailers purchased from FEMA [38]. In the following discussion to specific types of prefabricated shelters are discussed, Exo (B.1) and Epoch homes (B.2).

1) Exo (ReactionHousing.com/Exo)

The Exo housing unit is a shelter produced by Reaction that meets humanitarian needs especially in areas where disasters occur. Exo housing provides housing that can include private living, sleeping quarters, and a kitchen. It also stacks for efficient storage and transportation. One Exo can house four people with a climate-controlled environment. The Exo has a lifespan of 5 to 10 years at a cost of USD 5,000 per unit [20].

2) Epoch Homes (EpochHomes.com)

Epoch Homes, located in the United States, produces eco-friendly structures, using a modular design. The company has developed two versions of their homes that can be utilized in a disaster situation [33]. The first design is 28ft x 28ft. It contains two bedrooms, and a fully finished bathroom and kitchen. When the structure is placed on location, the dining/living areas and bedrooms are folded into place. During shipping, it folds to 11ft wide x 28ft long x 11ft high. It sells for USD 32,000, and although it does not fit in a shipping container, it can be transported below the deck of a ship [33]. The second design is a similar home that measures 15ft x by 36ft that can be folded to fit into two shipping containers. This model sells for USD 30,000 [33].

C. 3D Printed Shelters

1) WinSun (yhmb.com)

WinSun is a company in China that is using 3D printing to build houses and buildings. Using a 3D printer that is 150 meters long, 10m wide, and 6.6m high they were able to print ten 200m2 houses in a day at a cost of USD 4,800 each [1]. WinSun uses "recycled construction waste, industrial waste, and tailings. [They] produce a mix of cement and construction waste to construct the walls layer by layer, a process much like how a baker might ice a cake" [41].

2) Contour Crafting (ContourCrafting.org)

Contour Crafting is a technology developed at the University of Southern California that uses additive manufacturing to automate the construction of houses and buildings such as houses [10]. Their manufacturing process builds in the conduits needed for plumbing, electricity, and other necessary components. The technology is still in the research phase of development and we were unable to obtain primary or secondary data regarding the cost of producing a comparable structure that could be provided to victims of a natural disaster. Contour Crafting has suggested the potential application for using this technology in disaster areas [15].

V. DISCUSSION

Our results show that simple wood structures were provided for the least cost, see table 1. More advanced structures such as those made of steel had higher costs but also tend to have a longer lifespan. In the examples where complete cost information was available, the cost of traditional structures compared ranged from CHF 565 to CHF 9865. These case studies spanned several years from 2004 to 2012. The exchange rates have varied somewhat over the course of that time and it is difficult to compare exact costs using US dollars. If we use the current exchange rate, the comparable cost ranged between USD 597 to USD 10,423.

Prefabricated structures including Better Shelter, Exo, and Epoch Homes range in price from USD 1,250 to USD 32,000. These structures include features lacking in more basic structures, such as wall outlets and LED lighting in the Exo. The price for our prefabricated shelter examples does not include the price of shipping the units to a disaster location. Table 2 compares the costs of prefabricated shelter examples.

We were only able to identify two organizations that are currently using 3D printing technology to create housing structures. We were unable to obtain direct cost data from either organization for producing a comparable structure to provide for victims of a natural disaster. Secondary information regarding the cost of a 3D printed structure was found for a 200 meter-squared structure from WinSun at a cost of USD 4,800.

When looking at the cost of the WinSun example, this type of shelter falls within the cost range of the traditional structures that were compared as well as the prefabricated structures. However, similar to the prefabricated structures, to manufacture 3D printed structures would require shipping costs for a suitable printer to be transported to the disaster location.

TABLE 1
TRADITIONAL SHELTER EXAMPLES

Traditional Shelter Example	Materials Cost per Shelter	Project Cost per Shelter	Total Cost per Shelter (in USD using current exchange rate)	Time to Assemble	Estimated Lifespan
Bamboo (2009)	CHF 260	CHF 330	USD 623	3 to 4 days	1 to 5 years
Timber (2009)	CHF 350	CHF 500	USD 898	2 days	6 to 12 months
Timber (2010)	CHF 500	*	*	1 day	24 months
Timber (2007)	*	CHF 560	*	1 day	24 months
Timber (2007)	CHF 225	CHF 340	USD 597	2 days	12 months
Steel (2010)	CHF 1700	CHF 4300	USD 6339	2 days	24 months
Steel (2005)	CHF 4765	CHF 5100	USD 10423	3 days	5 years
Steel (2004)	*	CHF 1500	*	3 days	5 years

*Incomplete or unavailable data

TABLE 2
PREFABRICATED SHELTER EXAMPLES

Prefabricated Shelter Example	Cost of Shelter	Time to Assemble	Estimated Lifespan
Better Shelter	USD 1,250	4 to 8 hours	3 years
Exo	USD 5,000	2 minutes	5 to 10 years
Epoch Homes (example 1)	USD 32,000	*	*
Epoch Homes (example 2)	USD 30,000	*	*

*Incomplete or unavailable data

IX. CONCLUSION

The purpose of this study was to compare costs between traditional disaster housing and comparable 3D printed shelters. Our review of the literature lead us to the research question: How does the cost of using 3D printing technology to build temporary housing structures after a disaster compare with costs of current strategies for building temporary housing structures?

Shelters available for disaster management vary from very simple to elaborate. As previously noted, the cost per shelter spans a very wide range depending on the type of structure and the materials used in construction. The 3D printed structure example from WinSun falls within the range of shelter costs that we evaluated. However, due to the lack of available cost data on 3D printed structures, we were unable to draw significant conclusions.

As shown previously in Figure 2, different types of traditional disaster housing are needed at different stages of recovery. As an area of further research, we hypothesis that 3D printed shelters may be more cost effective if the 3D printed shelters are able to be utilized for multiple stages of recovery.

Several limitations posed challenges to our data collection. The first was the language barrier, which, in some instances, made interviews difficult. Another limitation was the low number of companies producing 3D printed shelters. We received very little primary data from the two major organizations involved in printing houses and thus had to turn to secondary data. The other limitation our research faced was lack of data. 3D printing is a relatively new technology and thus finding secondary data proved to be challenging. Implications of this are that although it was possible to present some financial figures for 3D printed constructs, the details for the cost involved are unclear. For example, the exact cost of materials and cost related to the potential use of construction waste from a disaster site are unknown. Similarly, since no company has yet used this technology for on-site 3D printing of disaster housing, it is not clear how much it costs to transport the printer. It was also not possible to get the companies involved to give estimates for these costs. Another aspect is the readiness of the 3D printed houses such as for instance whether it includes electric wiring and plumbing. Information on this was also not available, and again, note that no company is yet 3D printing disaster housing. It has been assumed that this is not included which makes it more similar, and thus comparable, to the other types of shelters.

The technology that has brought us 3D printing to use in real time also has the potential to save thousands, if not millions of lives across the globe. 3D printers can provide everything from housing, clinics and public service checkpoints to weather detection stations. USAID stated that weather stations can be placed anywhere they may be needed, for about USD 200, in order to predict weather events and reduce damage from them [4].

"In the aftermath of a natural disaster or war, affected areas may as well be on the moon…. [When] tens of thousands must do without critical items, like medical supplies, as the outside world mobilizes" [26, para. 4]. 3D printers can bring much quicker relief to suffering community members. James [26] noted that by cutting through a supply chain that takes too much time or is too unwieldy, 3D printers could be set up in countries and immediately begin providing shelter, prosthetic limbs, water purification systems, and other aid in a particular disaster.

Edwards [14, para 7] wrote that the technology provided by the company, Field Ready "combines 3D printing with low-tech innovation such as "hyper-local" manufacturing to provide aid workers and those affected by disasters with tools to help them overcome the weaknesses of the current system." The company discovered the importance of their technology after the earthquake of 2010 in Haiti; 3D printing is now known to reduce the devastating impact of such natural disasters because they can help on the ground.

"Field Ready says they hope to alleviate the problems by providing more direct, immediate technological intervention. In 2013 alone, 334 "country-level natural disasters" affected the world, occurring across 109 countries" [14, para. 11-12] and 3D printing is improving all the time. The next 'country-level disaster' can use 3D printing technology to alleviate the toll on humans and companies. The number of these companies will likely multiply as the need arises, as the threat of natural disasters and war continues to grow.

Further research on 3D printing capability should include durability comparisons and observable data from the scene of disasters in order to improve the technology and the response time. 3D printing is not just for urban dwellers seeking apartments; it can be used to save people before and after a natural disaster or other devastating events. Another aspect that should be included is health related information. For example, the FEMA trailers used after Hurricane Katrina caused health issues for many people due to emitted toxic levels of formaldehyde [38]. It is not clear at this point how 'healthy' 3D printed houses are or whether there are long term implications on the health of inhabitants.

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