3D Printing: A Future Collapse-Compliant Means of Production

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ABSTRACT

In areas of resource scarcity, 3D printing has the potential to provide an environmentally sustainable and collapse-compliant means of production. 3D printing can reduce waste, utilize local and sustainable printing materials, and create an extensive variety of objects to help localized communities produce goods in resource-scarce environments. The possibility of societal collapse provides an opportunity to discuss the future of 3D printing technology under the notion of collapse informatics, and to discuss current opportunities and limitations of 3D printing as a collapse-compliant means of production. Because of 3D printing's novelty and rapid development, it is difficult to predict the future of personal 3D printing technologies. 3D printer designers should use the present to evaluate a possible future of collapse and realize the industry's potential to become a collapse-compliant means of production.

CCS Concepts

• **Social and professional topics** → Sustainability • **Human-centered computing** → Empirical studies in HCI**;**

Keywords

3D Printing; Sustainability; Collapse Informatics; Additive Manufacturing

1. INTRODUCTION

The end of current global industrialization is far from desirable, yet plausible as a result of high resource extraction rates and global production [32]. HCI researchers are starting to prepare for potential collapse scenarios and develop sociotechnical systems meant to address adaptation and mitigation strategies during collapse [35]. Three dimensional printing (3DP) is an appropriate example of developing technology that can become collapse-compliant. 3DP and 3DP related technologies can reduce waste, promote re-use of materials, provide local and sustainable material options, create an extensive variety of customizable products, and localize production. These features allow 3DP to work in resource scarce environments and become a sustainable means of production. When addressing the future of 3DP development, designers should consider scenarios of societal collapse and develop 3DP designs for a potentially resource-scarce society. Even if collapse does not occur, collapse-compliant features of technology are useful in environments of limited resources such as underdeveloped countries and remote communities. Collapse-compliant considerations will not only improve 3DP's ability to adapt to future states of collapse, but also improve the current sustainability of 3DP technology.

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2. RELATED WORK

2.1 Collapse Informatics

For the past several hundred years, the world has encountered a relatively steady growth in economics, population, technological innovation, and standards of living. This growth is a result of humans persistently extracting natural resources and using them for an amalgam of different purposes such as nutrition, manufacturing, trade, and medicine. However, we are exhausting natural resources at a faster rate than the rate of their renewal, leading to consequences of economic growth [31]. As a result, many scholars have predicted a future period of decline in both economic growth and resource availability, possibly leading to a period of civilization collapse [21] [32]. There are a variety of possible scenarios as to how collapse can or will occur, with the more likely scenarios being tied to energy resource depletion. This collapse could lead to situations of limited societal cooperation, less centralized control, and less flow of information and resources [32]. Scholars have begun to look at technology development through a "limits-aware" lens and call for technology designs which promote responses to global change [31]. This field of research is known as *collapse informatics* and seeks to evaluate and design sociotechnical systems that can be sustained in a future of resource scarcity during a period of collapse [36].

2.2 The Rise of 3D Printing Technology

3DP, also known as additive manufacturing, is the process of making a 3D object typically by laying down thin layers of material in succession. This process empowers users to create a limitless array of objects on demand. Everything from organs to airplane parts have been created using 3DP technology [35] [38]. In the future, 3DP has massive potential to revolutionize the way we produce goods in a much more decentralized system. Since the beginning of its commercial sales two decades ago, 3DP has developed at a momentously fast rate. From 2007 to 2014, the global industry for personal 3DP grew over 211,000%, growing from 66 units to 139,584 units in sales [40]. The market for 3DP is unlikely to decline in the upcoming years and could potentially follow the same economic and societal pattern as the personal computer.

For the purpose of this discussion, personal fused deposition modeling (FDM) 3DP, or small-scale affordable printers meant for personal at-home design, is the main focus of inquiry for localized production. In a predictably scarce future, infrastructure will decay and industrial development may cease to support production on a global scale [14]. As a result, societies will become more localized, leading to more self-reliant and 'ultra-local' forms of production [37] such as the personal 3DP. However, industrial 3DP is still a critical component of 3DP innovation, and a market push for industrial 3DP innovation may also benefit personal 3DP innovation. Therefor industrial 3DP is evaluated for investment potential in 3DP technology development but is not evaluated as a future collapse-compliant means of production.

3. OPPORTUNITIES FOR SUSTAINABLE 3D PRINTING

3DP has massive potential to provide technological features to support development with limited energy and materials. In 2010, Pearce et al. outlined a set of ideal functional requirements and barriers to 3DP which provide sustainable 'village-level' fabrication able to comply with constraints of local community resources [26]. The idea of 'village-level' fabrication is easily extended to collapse informatics which seeks to produce more localized sociotechnical systems. These requirements include:

1. Inexpensive 3DP machines, ideally self-replicated and produced with local materials
2. Inexpensive feedstocks with local materials
3. Open source designs and 3D related software
4. Inexpensive and rapidly fabricated parts
5. Low, locally available, renewable energy
6. Open/free technical support and knowledge
7. Minimal negative effects on environmental and social health

Barriers to successful 'village-level' 3D printing. include:

1. Locally available printing materials
2. Print size and speed options
3. Material selection
4. Non-renewable sources of energy

The industry has rapidly grown since Pearce et al. presented these requirements, and many of the development barriers are being removed. The following section will discuss current sustainable 3DP features and how they remove barriers and provide opportunities for a collapse-compliant means of production.

3.1 3DP Materials

3.1.1 Material Waste Reduction

Compared to subtractive manufacturing, which creates objects through a process of removing material, the process of additive manufacturing (3DP) limits waste by using no more than the quantity of materials needed to create the product. Also, unlike other forms of manufacturing such as injection molding, 3DP has the ability to reduce infill of a product [16]. This can satisfy Pearce et al.'s requirements for minimal effects on environmental and social health. In manufacturing, "[c]ase studies indicate that up to 40% of the raw material-related waste can be avoided using 3DP while 95-98% of the unfused raw material can be reused," [18]. Even though the reduction in waste relates to manufactured and not personal 3DP development, this dramatic reduction in material waste provides incentive for current companies to invest in 3DP tools that provide a more profitable means of production.

3.1.2 Material Recycling

Additive manufacturing may limit waste production, but it is not completely waste-free. 3DP requires extra material to be printed as support to structures with objects containing angled areas or features built above empty space. There is also waste from failed prints, prototyping, and disposal. Often in personal 3DP, this excess material is thrown away, but at-home hobbyists and companies such as ReDeTec are creating 3D recyclers to re-melt and repurpose older 3D prints and support materials [28] [19]. This would allow a constant re-use of materials for users' current needs, notably reducing the amount of waste in the environment [30]. If 3DP continues to be self-constructive, new generations of the printer can be refurbished using recycled parts from pre-existing printers, supporting rapid innovation while dramatically reducing waste caused by rapid changes in technological innovation.

Material recycling is especially useful for products which have a short-term life span. For example, in the medical field, pediatric assistive technology such as prosthetics are inevitably abandoned after children outgrow their technology. 3DP-based prosthetics are highly customizable, and can be improved by implementing a constant recycle of material as the child grows. Therefore, 3DP can repurpose an obsolete item for a new and specialized need.

3.1.3 ABS and PLA Materials

3DP can create objects with an extensive list of materials including precious metals, plastic, steel, porcelain, aluminum, and nylon. The most prevalent personal 3DP materials are two types of plastic: Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). Because ABS fumes from melted filament can contain small amounts of hydrogen cyanide and carbon monoxide [29], it not an environmentally sustainable form of production. However, PLA is made of biodegradable products such as cornstarch and sugarcane, making it environmentally friendlier than ABS.

3.1.4 Algae Filament

Algae filament is a combination of wild harvested algae and PLA [1]. There are a variety of benefits to algae that make it particularly useful in a collapse-compliant system. Algae grows rapidly in comparison to other crops, grows in areas ill-suited for farming, can reside in sea water or brackish water environments, and produces O2 while reducing CO2 levels in the atmosphere [2]. This makes algae thrive in many different environments. For high productivity, algae need considerable levels of CO2 which can be supplied by CO2 emission-heavy places such as power plants [2]. Algae is also being used as an alternative bio-fuel for gasoline and diesel engines [1]. This low cost and low emissions alternative to petroleum based fuel provides high incentive for current industries to explore efficient algae production. Thus, 3DP filament can benefit from the increasing research in algae production already being established in algae biofuel research.

3.1.5 AgriDust Filament

AgriDust is a 3DP filament made out of six compost materials - coffee, peanuts, tomatoes, beans, oranges, and lemons - in combination with potato starch [10]. This filament can be used to make pre-existing compost into usable and naturally biodegradable objects. Because of its naturally high rate of biodegradation, AgriDust cannot be used for long-term needs: however, it could prove useful in cases of immediate disposal. The designer of this filament 3D printed a compost egg carton and a temporary flower pot to provide examples of consumables that can transition to biodegradable alternatives.

3.1.6 Repurposed Materials

3DP filament is also being produced from recycled trash leftover from previous plastic production. The companies TerraCycle and

3D Brooklyn recently announced a new filament made out of recycled chip and snack bags [23], and the company B-Pet sells filament originating from recycled PET bottles [6]. These advances in 3DP materials are exploring more locally sourced, environmentally sustainable options which repurpose older waste.

3.2 Renewable Energy

Personal 3DP is able to produce objects in rural areas and developing countries. When using energy sources such as photovoltaic technology, the cost of energy can be reduced and reach populations with limited to no electricity [26]. In the case of collapse, limited electricity availability could restrict or eliminate use of certain fabrication technologies. 3DP's relatively low energy consumption could sustain development when powered by alternative energy such as photovoltaic energy [16]. 3DP printers such as the RepRap are well within electric range of current commercialized photovoltaic systems, making these systems ideal for areas of limited energy [26].

3.3 Decentralized Production

'Containerization' is the global transportation of material goods through long supply chains, cheap energy and computerized statistics, inventories, and distribution systems [5]. Much of the world relies on this containerization construct for its material goods and is dependent on a large scale market system. In a time of societal collapse, there will most likely be a reduced flow of market goods on an international scale, eliminating much of the global industry system on which we depend. Birtchnell and Hoyle determined 3DP can offer an alternative form of production in areas of material poverty by removing economies of scale and, "eliminating the need for distribution almost completely," [5]. Whether it is a currently underdeveloped nation or a future collapsed society, this method can decentralize production and eliminate dependencies on global market trade, thereby supporting communities in the localized production of material goods.

3.4 Economic Motivations

Although future collapsed civilizations may have limited economic structures and manufacturing capabilities, current industries recognizing the cost benefits of 3DP have an economic incentive to increase research and development into 3DP systems before a potential collapse. One of the greatest strengths of 3DP is its ability to customize products with "no additional cost" [11]. This reduces the need for multiple tools and the replacement of machines when the design of an object is altered or customized. While Savonen points out "free complexity" is not completely true, compared to traditional methods of manufacturing, 3DP does have a distinct advantage in that it can create complex geometric figures with only one machine [30].

For underdeveloped countries, 3DP is an attractive option for manufacturing in local economies. 3DP's ability to construct with minimal infrastructure can stimulate local economies and reduce foreign dependencies [27]. This creates an economic incentive to increase production in underdeveloped countries, making collapse-compliant 3DP design more attractive and profitable to these current economies of production.

3.5 User Participation in Production

The economic success of low cost 'disposable hightechnology' and public access to digital fabrication tools like 3DP, CNC mills, and laser cutters have empowered users to modify and create their own material objects [36]. As a result, there has been a growing population of consumers becoming creators. This section will discuss the movement towards individualized production and their relation to sustainable 3DP.

3.5.1 The Maker Movement

The Maker Movement, as it has been coined, describes this rise in do-it-yourself (DIY) culture for personal development [17]. Observations in personal fabrication and online communities dedicated to DIY technologies could be an asset to localized technology development. In a collapsed civilization where skills and resources are limited, local communities will have to look at personal production and community efforts of development. If collapse were to occur in the next several decades, this growing culture of "expert amateurs" [25] could be beneficial to a collapsed society in need of localized production and innovation.

The industry surplus of low cost technology has sparked the Maker Movement [36]. If this industry surplus disappears, there will be limited opportunities for these modern makers to use surplus materials in a civilization of collapse. However, there are two outcomes of this movement which make it appropriate for this discussion. Tanenbaum et al. notes the new community of middle-class makers is "re-negotiating the social contracts around the production and consumption of technology" [35], thereby increasing societal interest in personal fabrication technologies such as 3DP. The rising demand will lead to greater developments to 3DP technology prior to a potential period of collapse. Secondly, there are makers in developing countries creating innovative new designs from other repurposed materials [35]. These limited resource maker communities can provide insight into future production techniques that can prevail in a collapsed community using alternative and repurposed materials.

3.5.2 Open Source and Open Sharing Technologies

Open source development allows society to collaborate and produce artifacts independent from legislative processes and/or massive changes in ideology [37]. This enables the digital community to heavily influence everyday practices that can evolve the design of collapse-compliant systems. It also allows localized and developing communities to share and collect ideas through online exchanges to produce technology historically inaccessible or undocumented. As a result, open source 3DP systems can leverage a variety of diverse communities and create more sustainable forms of technology [26].

Similar to open source, the presence of the maker movement in online communities has initiated widespread development of online sharing platforms that feature numerous DIY technologies. Online communities have revolutionized personal 3DP production by creating online repositories of 3D models. Thingiverse.com is an open-source design repository that makers use to share and encourage different forms of 3D innovation. The Thingiverse.com community has uploaded and shared over 485,510 models, dramatically increasing the amount of 3D models available to users.

3.5.3 Personal Motivations

The "Ikea Effect" is a cognitive state in which consumers place a higher value on products they create over alternatives [24]. An increase in personal value from personal 3DP creation can reduce waste and abandonment of certain products while increasing their lifespan, supporting a society of limited resources. However, it should be noted that the arrival of on-demand, low-cost, personal fabrication technologies like 3D printers may also increase waste as a result of users continuously printing recreational objects for enjoyment or out of immediate interest. But as previously mentioned, 3D filament recyclers will reduce wasted resources and empower users to continue printing with the ability to reuse objects' materials.

4. LIMITATIONS OF 3D PRINTING

Self-reliant and ultra-local forms of production should be a central feature of collapse-compliant sociotechnical systems. By increasing consumer adoption of personal 3DP today, 3DP industries can assimilate 3DP into everyday culture, supporting future systems of ultra-local production. However, there are barriers to both the current adoption of 3DP printing technologies and complete sustainability of 3DP. This section discusses barriers of 3DP systems which should be addressed to increase both consumer adoption and sustainability.

4.1 3DP Materials

Regardless of an increasing supply of alternative materials for 3DP filament, personal 3DP material options are still relatively limited. Thermoplastics like ABS and PLA cannot be used to create objects that will be subject to high temperatures such as kitchen supplies and electrical systems. There is also limited durability and stability with current materials. Plastics and alternative filaments may lack proper strength requirements for objects such as construction tools or objects undergoing a continuous cyclic load such as a gear in motion. Strength and durability of alternative materials for 3DP must be considered in order to become a viable material for production.

4.2 3DP Speed

Print speed is also a challenge for many personal 3DPs. An FDM personal 3DP takes an average of eight hours to produce a standard fifty millimeter cube. This is relatively slow and can dissuade current users from purchasing 3DPs. However, stereolithography (SLA) 3DPs are providing an alternative form of production which is must faster than FDM printing. SLA uses liquid polymer to create 3D prints and can be 25 to 100 times faster than the average FDM 3DP [12]. There are currently limited personal SLA printers on the market, but as SLA printers become cheaper and individualized for personal consumer sales, concerns over personal 3DP speed could be resolved.

Although SLA provides a faster alternative to FDM printers, there is limited research in the sustainability of SLA. SLA printing materials vary among manufactures and rely on different chemical reactions to change the state of the polymer. Some biodegradable polymers have been researched for SLA [33] and could be implemented during increased consumer adoption; however, there is limited research in how the increase in SLA production will affect 3DP sustainability.

4.3 User Purpose

Personal 3DP is in what Lipson and Kurman call the “Altair Phase”, a development phase similar to the first personal computer, Altair [17]. The market for Altair was limited to a pool of technically skilled consumers capable of assembling and maintaining their own computer. The same can be said for the first developments of consumer level 3DPs. First generation 3DP owners need some level of skill in 3DP maintenance, calibration, and 3D modeling software such as computer aided design (CAD). Each of these skills takes time and effort to develop and can be challenging for the average user.

4.4 3DP Usability

For 3DP to develop in today’s economy, it must resolve usability issues for non-technically skilled customers and design user-friendly systems better fit for the average household user. 3D modeling software is especially in need of further development. Although there is a variety of CAD software available for novice and expert users, modeling difficulties are experienced at all skill levels. Novice online systems such as Tinkercad are great for simple standard shape creations, but lack a user friendly way to make more complex and organic shapes [8]. This limits a user’s ability to produce the exact objects they need. Expert level software such as ExpertCAD provide advanced tools to make complex objects, but have a steep learning curve difficult for the average user to overcome [8]. Advanced commercial CAD systems also have their own set of geometric problems as a result of model complexities still being addressed by current CAD software developers [3]. If 3DP becomes prevalent in everyday use developers should address these modeling complexities and provide more usable and versatile tools for 3D model creation.

4.5 Societal Risk

From lifesaving 3DP production of organs, to life-threatening 3DP production of weapons, the media portrays 3DP with conflicting emotions. One of the most unfortunate and socially concerning 3DP topics highlighted by social media is 3D printed firearms. The successful creation of 3D printed guns has not only led to mass skepticism over the use of 3DP but a national debate on how 3DP will affect national rights [7] [13] [15]. Security threats to current industries is also a concern. In the future, Tanenbaum et al. predict other sources of conflict such as 3D printed spam and digital warfare attacks [36]. Continued negative media attention could affect the acceptance of 3D printing technologies in local communities.

4.6 Liability and Copyright

Copyright and patent laws will need to be addressed for widespread printing to be accepted by regulatory standards. By calling 3DP “the next great technological disruption,” Weinberg highlights the benefits of widespread access to 3DP, but warns 3DP communities about copyright and patent issues which will affect the future of 3DP [39]. Most notably, Weinberg states the possibility of 3DP restrictions to protect and expand intellectual property rights [39]. To avoid these restrictions, Weinberg encourages 3DP communities to promote widespread access and address policy issues now before 3DP creates a mass disruption in existing business models that will cause companies to attack on grounds of piracy [39]. These restrictions could lead to legal battles in the 3DP industry, potentially s production and sustainable development.

4.7 Economic Deterrents

In comparison to injection molding, a popular form of mass manufacturing, 3DP can produce initial products at a reduced cost in a shorter amount of time [4]. However, 3DP production levels cannot compete with the mass production capabilities of injection molding [9] [4]. Even though many scholars predict this will change in the future [9], current mass manufacturing economies do not have incentive to invest in 3DP technologies.

4.8 Unsustainable 3DP

Without a large demand for sustainable 3DP innovation, it is easy to imagine 3DP continuing unsustainable practices. ABS material is still frequently used in personal 3DP and will continue to emit harmful toxins until the demand for ABS declines. SLA printing can also suffer from increased chemical emissions if the market continues to grow and proper research on polymer materials is not conducted. Also, like many other mass technologies, 3DP is innovating at an extremely rapid rate, creating outdated legacy systems in a matter of years. Unless 3DP recyclers become more prevalent, this will continue to create the same cycle of increased e-waste most consumer technologies produce.

5. DISCUSSION

3DP in a collapsed society could take on many forms of production. Similar to Pierce et al.'s 'village-level fabrication' requirements [26], potentially key components to 3DP success in a state of collapse could include the ability to harness renewable energy, to be resilient or capable of self-reconstruction, and the ability to print with locally produced materials adaptable to different production needs. Ideally, these printers could also print using multiple types of materials and self-innovate by printing improved versions of their own parts. Today, personal 3DP is being used for a variety of recreational and non-recreational purposes. In a future of limited trade and infrastructure, we could see an increased interest in printing fundamental objects for survival such as tools for agriculture and construction. If 3DP recyclers and non-renewable energy continue to grow, the indefinite cycle of design and re-design will potentially eliminate wasted energy and materials. We cannot know for sure if or when collapse will occur, nor can we predict the future state of 3DP innovation. Nevertheless, by looking at today's developments, we can conclude there are significant features which make 3DP capable of sustainable and collapse-compliant development.

6. CONCLUSION

Sustainable innovation of 3DP could, "help achieve some of the most urgent environmental and resource goals facing the international community" [9]. While we are still living in a time of relative abundance in both physical and intellectual resources, the present is the time to innovate and develop collapse-compliant systems [37]. We should discuss the implications of 3DP technology, innovate for collapse compliancy, and steer the 3DP industry towards sustainable materials and designs. Integration of new technologies into current society takes time, but if we overcome limits to consumer adoption and design printers for collapse-compliancy, we can integrate a future mass integration of sustainable 3DP into everyday life. This will prepare communities for a resource-limited future and provide currently resource-scare communities an alternative means of production, improving technology's relationship to the earth and its limited resources.

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