Evaluating the Identity and Disruptive Potential of Additive Manufacturing: A Stakeholder-Focused Perspective

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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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Introduction

Additive manufacturing technologies (AM technologies), colloquially known as 3D printing technologies, are a class of manufacturing methods in which products are built up by depositing and fusing raw material in successive passes, or *additively*. For example, metal-based AM technologies like Laser Powder Bed Fusion (LPBF) successively fuse layers of metal powder using a scanning laser (Tian et al., 2020). In contrast, many traditional manufacturing methods are subtractive methods. That is, these methods start with solid raw material and form the product by cutting into the desired shape (Pereira et al., 2019). Although AM technologies have existed since the 1980s (Wohlers and Gornet, 2016), there has been an increased interest in the technology recently due to the potential advantages that AM offers over traditional manufacturing techniques. For example, at appropriate scales, AM is more resource-efficient than traditional methods. These advantages may allow for greater economic gains. Of note is the ability to reduce time to market, and also the ability to increase supply flexibility via on-demand manufacturing (Debnath et al., 2022). Aside from technical challenges in implementing AM systems at scale, there are also organizational and social challenges in employing AM systems. The literature on societal impacts of AM presents a wide variation of scenarios regarding its future, such as a transition from centralized to distributed manufacturing (Ben-Ner and Siemsen, 2017) and the incorporation of on-demand manufacturing with consumer information to achieve higher levels of product personalization (Jiang et al., 2017). This variation broadly seems to indicate uncertainty about the outcomes of adopting AM. Simultaneously, the promise of design flexibility and cost savings from AM technology has attracted interest from a wide variety of stakeholders, each with differing motivations for investing in AM. These stakeholders include, but are not limited to, aerospace manufacturers, biomedical companies, the US government, and auto manufacturers (Chang, 2016).

The broad cross-organizational interest in AM technologies and the variation of projections regarding its potential impacts seem to point to the claim that AM technology is a revolutionary technology, in the sense that it will dramatically restructure both the technical and social systems surrounding the manufacturing of products of all kinds.

I will evaluate the merits of this claim from a stakeholder-focused perspective. A variety of stakeholders, both directly and indirectly involved with the usage and promotion of AM technologies, will be considered. In particular, I will focus on the problems that these stakeholders face which make AM technologies an appealing solution, and possibly the barriers (both technological and social) that these organizations face in adopting AM. This analysis is intended to clarify in what industries the adoption of AM is more or less mature in, and evaluate the disruptive potential of AM in that industry. Social construction of technology (Pinch and Bijker, 2008) will be used to structure the stakeholder analysis. I will also consider some broader themes and trends regarding the development of AM that have become points of discussion in recent years.

Background on Additive Manufacturing

Despite the attention that additive manufacturing has received in recent years, AM is not a particularly new idea. Charles Hull is credited with working on one of the first AM technologies in 1980, which he called stereolithography. This process involved building products layer by layer by using UV light to cure liquid polymer into a solid product (Hickey, 2014). S. Scott Crump worked on developing fused deposition modeling (FDM), a system in which plastic polymer is extruded onto the build plate, and layered on top of and beside previous layers of filament to create a complete part. He submitted patents for precursors of this technology in 1992 (Crump, 1992).

Today, a variety of additive manufacturing methods exist, and are designed to work with different sets of materials and meet different functional requirements. Aside from the previously mentioned LPBF and FDM technologies, other AM technologies include Directed Energy Deposition, Binder Jetting, and Vat Photopolymerization (Shahrubudin et al., 2019). Each of these technologies can be further varied by the choice of material, the scale, and the application area.

The nomenclature of AM technologies reveals some facts about its development. Historically, AM has been used for prototyping and design, hence its traditional name, *rapid prototyping*. Compared to traditional manufacturing methods, AM reduces entry costs and removes the need for additional labor to obtain functional prototypes (Rayna and Striukova, 2016). However, there has been interest and shifts towards employing AM in production, as will be discussed later in the paper. However, some AM technologies are referred to as "3D printing" technologies. In this paper, both terms will be used freely. However, in connotation, "3D printing" is often used to refer to FDM-type machines employed by hobbyists, and the term "additive manufacturing" is reserved for industrial-grade machinery, often using metal powder (“3D Printing vs. Additive Manufacturing”, 2021).

Social Construction of Technology and its Applicability to AM

Social construction of technology (SCOT), a theory elaborated by Pinch and Bijker (2008), posits that the explanation of a technology’s successful adoption, or lack thereof, can be explained in social terms. Notably, SCOT rejects the deterministic thesis that the reasons for a technology’s success is solely due to its technological superiority, and contends that a non-linear "multi-directional" process of interactions between the technology, social organizations, problems solved by and caused by the technology ultimately drive the character of and the acceptance of the technology. Some relevant terminology from the SCOT paper is as follows. When Pinch and Bjiker refer to a *social group*, it may refer to formally organized institutions or not. The important point is that the social groups have a common attribute or attitude with respect to some relevant facet of the technological artifact in question. Then, each relevant social group faces some *problem(s)* as relevant to the technical artifact at hand. A detailed exposition of the social groups is necessary to understand which variants of the artifact tend to be most appropriate for addressing the problems faced by the social group in consideration. Also, understanding interactions between the social groups such as economic power, political power, marginalization, etc. are helpful in understanding how social groups exert influence on the narrative about what is the most important problem. Finally, Pinch and Bjiker also introduce some terminology that is helpful for describing how technologies eventually become established with firmer identities. Before a technology becomes established, many variants may exist which all serve different purposes. In this case, the technology has *interpretive flexibility*. In the choice of this term, Pinch and Bjiker not only mean that there are differences in how different variants of the technological artifact are designed and used, but also that the cultural interpretation, meaning, and value laden in artifacts is subject to interpretation, in particular from differing social groups. In contrast, a technological artifact is said to have *stabilized* when there is a prevailing design. The meaning of the artifact is not subject to interpretation, and the problems associated with the artifact appear to have "disappeared."

It is interesting to consider the application of the SCOT framework to AM technologies, as its development readily parallels the themes and directions of the SCOT framework. As explored briefly in the introduction, there are numerous stakeholders involved in the development and creation of AM technologies, ranging across a diverse set of industries, government agencies, and research facilities. There is also much to say about the potential impacts of AM on the consumer side. Each of these groups will have their own attitudes towards AM, and problems that they hope AM will address for them. It is interesting to consider the notion of interpretive flexibility and closure as applied to AM given the current information regarding its development. As mentioned, many variants of AM technologies exist, all of which are tailored towards different materials and essentially different applications. To carry out this SCOT analysis, we focus primarily on the description of stakeholder groups. In the framework of SCOT, the problems and context from these stakeholder groups are what characterize the identity of the technology and are intended to explain the technology's eventual success or failure.

Stakeholders

A myriad of stakeholders are involved with additive manufacturing. These range from users of the machines in industries such as aerospace and automobile, to hobbyists, and regulatory agencies. In addition, companies who manufacture the AM machines and companies who provide AM services are major players. Since an exhaustive account of all these stakeholders is impossible, we focus on describing a select few categories of stakeholder. In order, these are retail manufacturing, biomedical, aerospace, government, and hobbyists.

Retail Manufacturing: Accelerated Product Differentiation

The motivations of retailers in applying additive manufacturing can be illustrated by a few examples. The Swedish furniture company, IKEA, introduced mass-produced decor options in 2017 manufactured by Selective Laser Sintering (SLS). The product in question was a so called "mesh-inspired stylistic hand", with a high geometric complexity that would not be economically feasible by traditional techniques ("Brave new 3D printing world", 2017). IKEA collaborated with external manufacturers, such as Wazp, to realize the product. Shane Hassett, the CEO of Wazp, stated that "a couple of vital patents have expired in the last few years, making it possible for the industry to start producing cheaper materials, more... machines, and allowing us... to make 3D mass production accessible." Jakub Pawlak, an IKEA executive in charge of the project, stated that he sees four possible directions forward for 3D printing and AM at IKEA. *(1) Small decorative objects with little to no practical functionality and (2) "small life hacks."* IKEA Israel demonstrated the possible benefits of "small life hacks" by designing add-ons meant to assist people with disabilities for existing IKEA products (Fingas, 2019). *(3) Enables greater design complexity.* The geometric complexity enabled by AM can drive new product designs. *(4) Printing on demand.* Pawlak stated that on-demand printing, where printers might be hosted in IKEA stores to create products in accordance with customer demand, might be possible if the cost of printing and operations continue to decrease.

Adidas introduced a new line of shoes with 3D printed soles called "Futurecraft", which was manufactured in partnership with the 3D printing company Carbon. The company used performance data and foot scanning technology to drive the design of the shoe, indicating the possibility of personalized, data-driven design for their consumer products. This resulted in a sole with a complex lattice structure. In addition, 3D printing helped Adidas speed up its prototyping phase for the design of the sneaker, reducing the time to market from the typical 15-18 months to 11 months ("How Adidas Is Leveraging 3D Printing In The Footwear Industry - Manufactur3D", 2020).

A common thread that runs through both cases is that AM enables greater customization and design flexibility, enabling retailers to differentiate their products via novel designs or improved functionality. In both cases, the retail manufacturers also indicated interest in producing on-demand, custom-tailored products to meet individual consumer needs. However, this strategy does not yet seem mature. Both retailers also relied on partnerships with external manufacturing companies to achieve their design goals. For Adidas, AM also enabled faster product development and shortened lead time, representing the traditional strength of AM as a rapid prototyping technology.

On the other hand, AM seems unlikely to replace conventional manufacturing techniques in retail manufacturing for mass-producing large products. A Deloitte study (Murphy and Cotteleer, 2015) surveyed industry participants in a AM online course to uncover motivations and provide a framework for understanding the implementation of AM in industry. They identified two major tradeoffs that AM can fundamentally restructure. First, *capital vs. scale*. One key benefit is that there is less initial capital required to reach an economy of scale with AM as compared to traditional manufacturing techniques, which makes AM suitable for lower-volume production. However, at mass-production volumes, the economies of scale from traditional manufacturing techniques beat out the savings from AM. Second, *capital vs. scope*. One AM machine can manufacture many different kinds of products without requiring extensive reconfiguration of the machine. This can reduce production costs by removing the need to buy and customize different machines for separate product lines. These observations seem to indicate AM's strength as an on-demand technology for manufacturing add-ons, customized parts, and bespoke products; rather than wholly replacing traditional manufacturing streams in the retail sphere. It provides additional flexibility that traditional mass-production techniques lack, but cannot yet scale at high volumes.

In addition, Hohn and Durach (2021) explored the possible impacts of AM in the apparel supply chain, again considering the case of Adidas. Originally, Adidas planned to host its new "Speedfactories" in Germany and the US using AM as the core manufacturing technology to meet demands for fast delivery and high customization. However, three years later, the factories were off-shored and moved to be closer to their Asian suppliers. Drawing on this anecdote along with survey data collected from experts, Hohn and Durach argue that AM is poised to reinforce the control that major retailers have over the industry, and push towards further price drops and faster product cycles, resulting in a negative outlook for labor conditions in the Global South. They arrived at this conclusion by asking the experts within the study to assess several hypothetical scenarios, e.g a "complementary-use scenario" where AM is used to support current production systems in the Global South, and a "reshored-production scenario" where AM production happens directly in wealthy consumerist nations within the Global North. In both scenarios, the experts generally agreed that overall AM would lead to tighter control. This is in part due to the "captive" governance structure of mass apparel industries, where suppliers must deal with short production timelines and high costs for exiting agreements with producers, allowing producers to unilaterally set favorable terms for themselves and capture productivity gains from AM while pushing towards faster cycles. While the study is admittedly still speculative in nature, it shows how AM might not always result in good outcomes for all stakeholders involved, and that the narrative focusing on futurism and product efficiency might be to the detriment of those who do not have a say in the design and implementation in the manufacturing processes and supply chain governance system.

Biomedical: Patient-Specialized Care

There is a great deal of interest and activity in the application of AM to the biomedical industry. Although only 5.6% of participants in the aforementioned Deloitte study (Murphy and Cotteleer, 2015) were involved in the life sciences and health care industry, 23.6% of participants indicated that they were interested in healthcare and medical applications of AM. The study also noted that in 2013, medical applications accounted for the largest segment of AM-related revenue.

Kumar et al. (2021) identified some application areas of AM in the biomedical industry. *(1) Tissue engineering*. There has been interest in developing special AM systems capable of printing scaffold tissue and artificial tissue to aid in regeneration and eventually to replace missing human tissue, e.g bone or organs. *(2) Patient-specific surgical models and tools.* To aid in surgical procedures, models of the patient's organs and tissues can be reconstructed and printed so that surgeons have a chance to practice before operating directly on the patient. *(3) Custom made* *prosthetics.* Prosthetics and implants can be manufactured on demand to suit the individual needs of each patient. *(4) Drug delivery systems.* AM technologies have also been used to print tablets, capsules, and dermal patches.

It can be seen from these application areas that the flexibility and customization of AM methods are a major selling point for its application in the biomedical industry. Kumar also noted that the inability of AM to scale to mass-production volumes is not as much of an issue in this application area as it is for retailers, as the requirements for prosthetics, tools, and surgical models necessarily change from patient to patient.

An illustrative example is the case of hearing aids. A 2017 article reported that 3D printing became the dominant method for manufacturing hearing aids (Scott, 2017). Customization and manufacturing precision was one of the major drivers behind this shift. Patrizia Richner, a digital manufacturing engineer working at Sonova, noted that hearing aids need to be custom-designed and fit to the needs of each individual: "If a hearing aid is 100 microns too large, your ear will feel the difference...it needs to be as discreet as possible - that depends on your ear canal shape." There is no real opportunity for economies of scale to allow mass-produced options, as the article notes "an actual person creates the model for each ear." However, it is important to note the scale and limited scope of this shift to 3D printing. Sandström (2016) argues that the introduction of 3D printing into the hearing aids industry was fundamentally non-disruptive and did not change the business dynamics of the industry. One observation is that there are two types of ear implements, behind-the-ear (BTE) and in-the-ear (ITE). ITE models necessitate custom fitting, and thus gain significantly from the usage of 3D printing. In contrast, BTE models do not require the same level of customization as ITE models and so can be mass-produced without 3D printing (“How 3D Printed Hearing Aids Silently Took Over The World - 3DSourced”, 2021). Additionally, Sandström (2016) argues that since the incentives for transition were clear and the wider socio-technical system was well-established and well-consolidated, 3D printing resulted in essentially no changes to the structure of the industry aside from a minor "destruction of competence" as technicians adapted their technical skills to use the 3D printing machines.

Aerospace: High-Complexity Low-Volume and Certification Challenges

Aerospace designers and engineers face several (possibly competing) objectives when deciding on their manufacturing strategies, as summarized by Blakey-Milner et al. (2021). A fundamental property of aerospace applications is that generally most projects are "high-complexity, low volume systems," requiring maintenance and "sustainment" over their lifetime of use. In addition, manufacturers and designers face regulatory and monetary constraints in producing new aircraft. It is desirable to create new designs that are as lightweight as possible to reduce future fuel costs and increase range, but this costs extra engineering hours and can pose a risk in schedules with tight, inflexible deadlines. New designs must be certified to be safe and quality of resultant parts must be controlled, especially for mission and safety critical applications. Additive manufacturing methods such as Laser Powder Bed Fusion promise to address many of these objectives. AM is inherently suitable for high-complexity low-volume manufacturing, and the lower cost required to design and prototype new structures enables a faster iteration towards appropriate designs. Its ability to handle complex designs enables new innovations and can enhance functional performance. AM promises to reduce cost by being more material-efficient, as unused powder feedstock for AM machines can be more easily recycled than raw material from traditional manufacturing techniques. Currently, the primary driver of AM in the aerospace industry is the ability to reduce lead times. Another major application area is to address repair and spare parts. Being able to manufacture spare parts on demand precludes the managerial overhead needed to manage an inventory of spare parts, and also enables the repair of legacy aircraft for which parts are no longer in circulation. In addition, AM can be used to repair existing parts. All of these advantages can result in signficant cost savings.

A critical challenge for AM in the aerospace industry is the certification of parts. Aerospace vehicles are subject to scrutiny from multiple regulatory bodies, such as the FAA. A certain standard of quality is required for manufacturing techniques to be approved in usage for production. However, AM technologies can still be subject to undesirable variability, hindering certification efforts. A major topic of research in this area is to develop novel methods for controlling and monitoring AM processes to control quality and variability (Frazier, 2014). Improvements in this area and in the underlying AM processes have advanced sufficiently to the point where AM is no longer used just for prototyping. From 2010 to 2020, use of AM has expanded to the point where it has been used to fabricate mission-critical components (Blakey-Milner et al., 2021).

Government: Policy and Law

Policymakers from multiple countries are commenting on the potential of AM to disrupt industries and enhance economic competitiveness. In the 2012 State of the Union, President Obama commented that additive manufacturing could "revolutionize the way we make almost everything." (White House, 2013), and the Biden Administration outlined an "AM Forward" plan in May 2022 to promote additive manufacturing usage in the US (White House, 2022). The Chinese government's Ministry of Industry and Information Technology outlined a Additive Manufacturing Industry Development Action Plan in 2017, with the aim of building an AM industry worth roughly $3 billion by 2020 (Haria, 2017). Accordingly, these governments have taken steps to promote the development and integration of AM into their national economies in order to boost their competitiveness in the global economy. As Bonnín Roca et al. (2016) puts it, "...a broad and competitive manufacturing sector is crucial to a robust economy and that to remain competitive a nation must invent and master new ways of making things."

At the same time, governments face a challenge in regulating growing technologies like AM without stifling their progress. Bonnín Roca et al. (2016) provides an illustrative commentary on the tension of supporting commercialization of an immature technology, and focuses on US policy for metal additive manufacturing in the aerospace sector. In this area, the US government has funded several National Network of Manufacturing Innovation institutes. One such institute, America Makes, focuses on metal additive manufacturing. Roca argues that in order to effectively tackle the problem of standardizing and certifiying AM processes, the US government should not only fund additional research into the basic properties of AM processes, but assist in compiling and distributing this scientific knowledge to all manufactures. Roca notes that otherwise, likely only large private firms with the necessary capital will be able to take on the necessary research, and they have little incentive to share the information with potential competitors. Thus, by funding organizations which aggregate and disseminate the results of research in AM, government can act to accelerate development. Basic research in the area of standards and quality can also inform legislation and regulation for AM, as many participants at a National Institute of Standards and Technology (NIST) workshop in 2016 felt that regulatory agencies should lead efforts in qualification frameworks for AM (Hrabe et al., 2016).

In addition to developing the technology itself, policymakers have considered the need for training a labor force of AM engineers. Simpson et al. (2017) summarized key points from a National Science Foundation (NSF) workshop that gathered participants from academia, government and industry to discuss educational needs for AM. A few key recommendations were presented. Some of these recommendations focused on AM curricula themselves. They suggested that the curricula should explain the relationship between AM processes and resultant properties so that future engineers can select the most appropriate AM process, and emphasize the philosophy of "design for AM," where products are designed for maximal compatibility with AM processes. Others were focused on outreach and K-12 education, suggesting the promotion of 3D printing and maker-space activities in local communities in schools to boost awareness and enthusiasm for 3D printing and AM related technologies.

Governments also face a challenge in regulating new crimes associated with AM technologies. For example, consumer end 3D printing machines now make it feasible for owners of 3D printers to fabricate unregistered firearms, which are more difficult to detect and regulate. There are concerns that these firearms may increase incidence of violent crime. In 2013, Cody Wilson used a 3D printer to fabricate a firearm and provided a video demonstration on YouTube. He published the design files on file-sharing websites, where it was subsequently removed due to security concerns (Walther, 2015). This leads into another related security concern for 3D printing technologies: digital file distribution and piracy. As 3D printing only requires a digital file describing the design for fabrication, there have been concerns that design theft and copyright violations will increase with the use of the technology, potentially causing significant losses to businesses

(Depoorter, 2013).

Hobbyists, Social Movements, and Public Discourse

3D printing has been associated with the so called "maker movement." Broadly, this term refers to the "growing number of people who are engaged in the creative production of artifacts in their daily lives and who find physical and digital forums to share their... products with others" (Halverson and Sheridan, 2014). Dale Dougherty is often credited with beginning this movement, starting roughly with the first edition of the magazine *Make* published in 2005 (Fernández, 2015). Practically, the movement is differentiated from prior eras of craftspeople by "three key characteristics: the use of digital desktop tools, a cultural norm of sharing designs and collaborating... the use of common design standards... as well as the emergence of cheaper and publicly accessible 3D printing tools combined with a "renewed interest in local goals and resources... " (Halverson and Sheridan, 2014). In 2012, the market size for 3D printing products and maker-related services was estimated to be $2.2 billion. The movement also has some key philosophical goals as well. One key goal is to shift consumerist identity and attitude towards self-production and ownership, echoing a long-standing American cultural ideal of rugged individualism. In a 2011 TED talk, Dougherty played a video clip that asserted "Of all things Americans are, we are makers." (Dougherty, 2011) Another ideal is to democratize production and innovation: the novelty of 3D printing need not be relegated to secluded labs, and breakthroughs are potentially achievable by everyday people. Dougherty claims that this movement is intended to be universalizing in the sense that the maker identity can "descri[be] each one of us, no matter how we live our lives or what our goals might be." (Dougherty, 2012)

Interesting insights of 3D printing in the hobbyist space can be derived from the case of RepRap, an open-source 3D printer designed to be capable of self-replication and thus democratize and distribute the means of production into the hands of everyday users. Söderberg (2019) explored the case of RepRap and subsequent commercialization of a derivative of the printer through the lens of labor process theory. The fundamental argument by Söderberg is that the open-source and distributed nature of the maker movement, where designs are intended to be freely disseminated and production can be distributed across a wide network of hobbyists linked by online forums, can actually be exploited and utilized by startup firms and venture capital. As this labor relation becomes formalized, labor conflicts and antagonism reproduce themselves within the community of makers.

For example, initially the RepRap production model was intended as follows: from a small initial "factory" of four machines, RepRap parts would be manufactured and sent to other users at minimal cost. These users would then assemble their own machines and repeat the process, serving as relay points for the spread of the machine. However, this intent was co-opted by market mechanisms. Some users instead opted to purchase pre-fabricated parts on online marketplaces, and took advantage of offers for minimal-cost parts by upselling them and turning a profit. So, the ethos of free sharing morphed in to one of "micro-entrpreneurship," and capital eventually concentrated into two firms, Bits-from-Bytes and Makerbot Industries. In return for capitalizing on the open information and innovation from the community, these firms provided ready-to-assemble 3D printer kits for sale which lowered the barrier to entry for new consumers. With further centralization, some producers returned to casting for manufacturing additional 3D printer components rather than printing, and the hobbyist market is seeing an increase of commercial, closed-source 3D printers squeezing out hobbyist self-employed entrepreneurs. This case clearly illustrates the difficulty and dangers of a technologically deterministic approach to constructing social systems: rather than gaining ownership and democratizing the means of production as hoped, labor antagonism and profit motives simply reproduced themselves within the social system and began squeezing out hobbyist-entrepreneurs.

Stein (2017) provides a fascinating perspective towards interpreting the economic, political, and social context around 3D printing technologies. In a similar spirit to SCOT, Stein identifies 3D printing as a "social phenomenon operating within the political imaginary." In this sense, the actual underlying technology is separated from the idea it represents as a "political imaginary" - what it promises and the discussion the artifact evokes is what drives narratives rather than necessarily the artifact itself. As 3D printing prompts (frequently utopian) imaginations of the future, she focuses on three particularly dominant narratives of 3D printing: "the maker-as-entrepreneur, the economic revival of the nation state, and commons-based utopias." The maker-as-entrepreneur narrative echoes the assertions by Dougherty: 3D printing will be a tool for individuals to design their own products and empower themselves to be entrepreneurs. The economic revival of the nation state narrative, primarily focused on the Global North, envisions a return of offshore manufacturing back to American and European coastlines, precluding the need to outsource to countries with strong mass-manufacturing sectors like China and India. In stark contrast to the previous two, the commons-based utopia is more analogous to the original mission of the RepRap: a system in which local communities and individuals control the means of production and design, ideas, and skills are shared freely. There is no longer a need for dependence on mass-produced products concentrated in large corporations, and individual citizens are in control of creation and consumption. The effect is to create a socialist society "without all that messy and dangerous revolution stuff." (Bowyer, 2011) Despite the political incompatibilities of these vision, Stein highlights one critical thread that passes through all three of these ideas: the emphasis on design and production as a critical component for reshaping society. Stein takes the fact that these ideas have entered mainstream discourse as an indication of the growing public awareness of the power of design.

Discussion

The comparison of the usage of AM in different industrial contexts reveals a few key insights. First, usages of AM thus far seem to gravitate towards high-complexity low-volume applications, producing custom-made or high-end consumer products. Economies of scale make it economically unattractive to use AM to replace traditional mass-manufacturing techniques, making it unlikely that AM will overtake traditional manufacturing for mass production. From the cases considered, it seems more likely that AM and traditional manufacturing will coexist, with AM serving to cover up major deficiencies plaguing traditional manufacturing processes, such as switch-over costs, spare parts inventory management, and customization. In this sort of scenario, AM is not necessarily revolutionary or disruptive technology, and serves primarily to enhance efficiency in existing socio-technical systems for manufacturing.

How can we understand the scope of adoption of AM in some domains versus others? The cases that have been presented so far, combined with the lens of SCOT, illustrate the myopia of a technologically deterministic approach to understanding AM. Although AM technologies did indeed come to dominate a specific sector of the hearing aids market due to the design needs of hearing aid manufacturers, organizational consolidation and a relative lack of the need for further product diversification resulted in minimal change to the organizational structure of the industry. Also, even though RepRap's proponents imagined AM technologies as a communitarian effort driven by open sharing, cooperation, and ownership of the means of production, the open nature of the project was instead co-opted and exploited by market forces, pushing the original hobbyists (who by then had adapted as hobbyist-entrepreneurs) towards the margin of the industry. In addition, the analysis by Hohn and Durach (2021) also indicates how the increased efficiency for bespoke product designs enabled by AM may not necessarily result in desirable outcomes for labor. So, the assertions that "AM is a revolutionary technology" need to be qualified: *in what industry? In what domain?* Only after carefully examining the incentive, governance, and communication structures of organizations and the affiliated stakeholders can complete accounts of AM's growth be developed.

In this sense, it is interesting to contrast the communities around the aerospace/biomedical domains versus the hobbyist/retail domains. In one area, the culture and norms are built by researchers, regulators and engineers, and in another, by looser informal communities of entrepreneurs and enthusiasts; the activity of building norms is a path towards stabilization. Regulatory activity for AM in the aerospace and biomedical domains is perhaps the most explicit method by which stabilization happens. However, evidence suggests this consensus is still building in the biomedical industry. Chhaya et al. (2015) noted that many research groups in biomedical applications of AM tend to come up with their own definitions and conventions, making it difficult to compare and evaluate merits of one research work versus another. In contrast, Söderberg (2019) noted that hobbyists involved with the RepRap project communicated and built conventions via the use of online forums affiliated with the project.

So, is AM a revolutionary technology? To evaluate this claim, we should consider some more specific sub-claims. *Will it restructure human organization and society as we know it?* Posed this way, it seems unlikely. The cases of RepRap and the ear implant industry show how AM's potential to disrupt industries depends quite strongly on the relevant organizational structure. Even from a more technological standpoint: *Will it become the dominant manufacturing method?* Also unlikely. The investigations into the retail, aerospace, and biomedical industries indicate that currently AM is only economically competitive for low-volume high-complexity batches, and cannot match the economies of scale afforded by traditional manufacturing techniques for mass production.

Instead, I'd like to argue (a la Stein) that the most unique and disruptive aspect of AM is how the technology enables new conventions and norms around design. Almost all the evidence we gathered from the stakeholder analysis has the thread of design running through it. The primary benefit or use scenario for AM often was not to replace TM or even to become a dominant method manufacturing method for end products, but rather to drive new and highly performant designs or unique, personally tailored products. Furthermore, the emergence of affordable and practical AM technologies catalyzed the formation of new identities linked with design in the "maker movement," and spurred the emergence of new narratives envisioning how control over design could influence human organization. Educational initiatives from the government aim to bring these ideas to a new generation of engineers. In this sense, it's not only the technological artifact but how the essential ideas of AM - building a part generatively rather than subtractively, on demand, directly from a digital design - can shape conceptions of "what's possible" both from the technological standpoint and from the standpoint of organization. This pushes innovation by opening the door to new and possibly disruptive products and technologies, and also spurs imagination about new ways of living, as elaborated by Stein. It is also interesting to think about the contextualization of design with advancements in information technology and artificial intelligence. A design can be thought of as an idea or a type of data, which in turn can be processed and disseminated via digital technologies. Furthermore, additive manufacturing technologies reduce the economic barrier between ideas and a physical realization of that idea, possibly further blurring the differentiation between the physical and the digital. In this way, additive manufacturing not only has the potential to change norms and conventions about design, but also interface with ongoing disruption of social thought by information technology and artificial intelligence.

Conclusion

In recent years, the emergence and steady maturation of AM technologies has prompted many to comment on its disruptive potential, and it has been much-heralded as a futuristic technology which will restructure human organization and enable new and innovative advances in product design and in engineering. In this work, we evaluated the identity of AM through the lens of the social construction of technology framework proposed by Pinch and Bjiker (Pinch and Bijker, 2008). We found that although additive manufacturing indeed has driven significant innovation in a broad variety of industries, it is unlikely to replace traditional manufacturing methods or even necessarily disrupt existing business and social organizations. However, the ability to enable complex design and manufacture a wide range of products has lent AM technologies a great deal of interpretive flexibility. This flexibility has captured the imagination and interest of governments and citizens alike, and so in this way AM takes on a life beyond just the technical capabilities in political imagination. In this sense, we conclude that AM may not directly restructure human organization and economies as envisioned, but might change norms and conventions around design, production, and consumption. Future work might consider exploring this from a more quantitative perspective, e.g by surveys. Linking AM to developments in AI and information technology, and how AM shapes identities related to production and consumption could also be considered.

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