The Implications in Design of Rapid 3D Design & Manufacturing

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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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Background

Three-dimensional (3D) Printing is an additive manufacturing technique created by Charles W. Hull in the mid-1980s (Hoffman, 2020). This technology, in essence, is a manufacturing process that lays layers of material down one at a time in order to create a physical three-dimensional model. This approach takes virtually all of the human error involved in traditional manufacturing out of product fabrication due to the fact that the only requirement to start a print is to upload a three-dimensional model created in 3D Computer-Aided Design (CAD) software and select the desired material.

Introduction

Additive manufacturing can be used by individuals and corporations alike in order to create both prototypes and products for sale. Furthermore, the nature of the additive manufacturing process allows designs to be created that were never feasible before with the use of a singular machine, such as constructing hallow shapes and hexagonal support structures within designs. Due to the significant impact that 3D printing has had on the manufacturing process since its development, engineers experience an environment in which the design process is revolutionized in terms of time, process, cost, and sustainability. As a result, designers learn how to think and design differently with these products, and there is room for study on how this is affecting engineers and society.

Advantages and Disadvantages Surrounding 3D Printing Technologies

In order to understand how the design process changes through this machinery, it is important to understand the benefits and shortcomings of 3D printing. One benefit provided by this technology is its ability to optimize the production process. Iterating on designs by machining or fabricating parts from metal or plastic stock is costly compared to additive processes (Formlabs, 2019). In order to prototype a design by fabricating metal parts, skilled operators must invest significant time into the production. This decrease in cost and labor requirements allow 3D printing to become a more viable option in order to evaluate fit and functionality of new designs. Furthermore, traditional manufacturing capabilities can also result in an imperfect result due to equipment issues or misunderstandings, or a certain design can require specific pieces of equipment that are not readily available. 3D printing can solve these drawbacks due to the fact that misunderstandings are a nonissue within the bounds of this technology and its ability to create so many designs rid the need of further machining (Zurmehlyand, 2019). Similarly, there is no increase cost for design complexity, encouraging designers to experiment with more complicated designs than with previous manufacturing. 3D printing increases the potential materials used within manufacturing and also allows the user to select the level of detail desired. Not only do these materials increase the diversity of product functionality and allow it to survive different environments, but they also increase savings drastically (Lipiec, n.d.). For example, if a prototype is made to only check its fit and functionality, a very cheap and readily available material and low print resolution can be used, incorporating a lower price for manufacturing into the build because high print resolution is not necessary for the majority of prototypes. For these reasons, in addition to its ability to save time due to its fast-paced means of production, 3D printing plays a critical role in terms of technology involved in the creation of a prototype.

The increase in demand all over the world for customized products and manufacturing has caused the 3D printing industry to skyrocket, particularly as the technology develops and more solutions become available on a sustainable level. For example, during the COVID-19 pandemic when many hospitals had equipment scarcities, the ability to rapidly manufacture on-demand solutions for a variety of purposes allowed many businesses to address these shortages with 3D printing. According to the FDA, “Non-traditional manufacturers and community responders have helped address shortages and gaps in medical supplies during COVID-19, and yielded millions of pieces of PPE (such as masks and face shields) and other 3D-printed medical accessories” (FDA, 2020). Due to its ability to help fight unpredictable issues such as this, the value of 3D printing cannot be understated.

The History and Evolution of 3D Printing

Due to the fact that 3D printing technologies have a direct impact on the way that engineers think and design, it is important to consider how these manufacturing capabilities evolved over time and the effect that significant developments have made in terms of human thought. Even in recent years, the tool manufacturing process has been used widely for many decades; a process which consumes a lot of material and time. This method generally requires the involvement of several engineers to manufacture even a small and simple prototype, or at a minimum require tooling on multiple machines. This is not affordable to all businesses, and contracting out machining processes can risk extended lead times and increased expenses (Fenton, 2019). Access to 3D printing greatly reduces these risks, and generally requires only one machinist or operator to produce a fully functional prototype.

In recent years, technical innovations in the field have halved costs while delivering twice the performance when compared to traditional manufacturing processes (Shepherd, 2020). This has allowed engineers and designers alike to be able to experiment with multiple different prototypes to physically test performance and functionality more freely as a result of the 3D printed models being low-cost in the current era of manufacturing. Engineers are required to get less financial approval for 3D printing due to its inexpensive nature, and thus can maintain a more free-range sense of design compared to traditional strict guidelines inhibiting creativity set in place to avoid risking a failed prototype. If a 3D printed prototype does not achieve its desired functionality, design iterations can be rapidly implemented using CAD design software and a new prototype can be acquired within hours. With this method, novel design iterations are far less expensive to build and test compared to manufacturing methodologies of the past.

In terms of where 3D printing technology is headed, in 2018 HP launched Metal Jet technology; the world's most advanced 3D printing technology for high-volume manufacturing of production-grade metal parts. It delivers mechanically functional parts with up to 50 times more productivity than other 3D printing methods, and at significantly lower cost compared to other binder jetting systems (EDACafe, 2020). This technological advancement follows the 3D printing industry's trend of allowing prototypes to obtain a wider breadth of functions while simultaneously decreasing production costs and allowing more complex geometries to be fabricated. This furthers the extent of designs that engineers can develop and increases prototype potential within the realm of design. For example, prior to this technology engineers could not rapidly manufacture prototypes that required a certain strength or durability to maintain its functionality. Rather, metal parts required a long process of multiple machinists and processes that could become very costly. With this development, however, engineers are able to create stronger, more versatile prototypes using the same methodologies for plastic parts. As a result, creativity can be implemented into more stringent design requirements such as those used for metal parts, overall changing the design process that engineers and artificers use.

Design with and without In-House 3D Printing Capabilities

Life as a designer is very different when lacking in-house additive or subtractive manufacturing capabilities. In the summer of 2018, I was an engineering intern at Cadence Inc, a contract manufacturing company that mass produces advanced products, technologies, and services to companies worldwide (Cadence, 2020). I had access to highly-valued 3D printing and CNC machining equipment, allowing me to witness how beneficial these machines are by saving time and money. 3D designs were created, printed, and brought to life as functioning prototypes within hours.

By contrast, in summer 2020 I interned at Rivanna Medical, a small biomedical company that did not provide access to a 3D printer. The design work was virtually identical, but once a 3D design was finalized, I compared different outsourcing 3D printing companies' lead times and costs to discover the best option. This time-consuming process included researching costs of shipping, materials, and material performances. At Cadence, the only manufacturing expense was material cost, which tended to be a few dollars per project. At Rivanna Medical, even small prototypes could cost upwards of $200. Because I was creating multiple prototypes, this proved itself to be a significant expense to the company due to its small startup nature, especially considering there were multiple employees creating prototypes for different products within R&D. Because of this, there was an emphasis on using very cheap materials, causing prototypes to be far weaker and less durable than if additional time had been spent finalizing the design before fabricating a physical prototype. More importantly, contracted parts could take more than two weeks to arrive. In 3D design there is often a fit or function problem that the CAD model does not reveal; edits must be performed to make a fully-functional prototype. It wasn't uncommon to wait weeks for delivery only to learn that the prototype didn't work as expected.

Conversely, if my Cadence design did not function properly, I would simply edit my 3D model and have a fixed prototype within hours.

Furthermore, access to 3D printing machinery changed my designing approach as a whole. Traditional subtractive manufacturing does not allow for certain manufacturing techniques that 3D printing allows, such as forming hollow parts and honeycomb structures. This is because additive manufacturing assembles parts layer by layer whereas subtractive manufacturing must remove material in a specified orientation. This can allow for many novel designs and characteristics to be considered, especially when considering their lightweight nature. In my own experience, particularly as an early designer, I would frequently design parts to be milled without considering the ease of manufacturing related to my design. As a result, I would often design a part with complex contoured geometries, thin-walled features, and slanted walls not realizing that these were often costly and infeasible within the confines of subtractive manufacturing. This served as a learning experience for me, and when designing parts for the mill or CNC machine I now ensure that my design incorporates straight-lined features that can be machined with a drill bit on only the top surface. With access to a 3D printer, however, my options are far less limited as I can incorporate virtually any geometries I like on multiple planes at once. This allows me to brainstorm multiple solutions simultaneously whereas my train of thought tended to be more restrictive when using subtractive manufacturing techniques.

The Impact of 3D CAD Modeling Software on Engineering Design

When considering the impact of 3D printing on society, it is imperative to consider the thought and design processes of engineers and designers, and how they are impacted by this technology. Therefore, it must be considered how a reliance and accessibility to 3D modeling software impacts design and engineers' thought processes as a whole. Because certain designs that 3D printing allows cannot be produced with subtractive manufacturing methods, engineers must tailor their designs using 3D CAD software to a specific means of fabrication. Using subtractive manufacturing, designers must consider ease of manufacturability, namely what shapes and contours are allowed by the process. On the other hand, 3D printing can create virtually any conceivable design provided that the resolution, or print quality, meets the design's standards. One study conducted at Yonsei University tasked two groups of participants with a design test, giving one group access to 3D modeling software and require the other to use a conventional sketching design method. When observing the design processes of engineers using CAD modeling software, it can be seen that "it is a constant challenge for them to introduce creativity into their design projects while meeting the necessary constraints associated with the object to be designed" (Lee et al, 2018). Furthermore, it was found that designers using CAD software participate in increased cognitive design actions: the experiment noted 669 actions for the conventional sketch method and 953 for the 3D modeling software. These actions include aspects of design such as making a cognitive analysis of the task, validating design through prototyping, and the study of one's own work (Yaagoubi et al, 2008). When considering the relationship between cognitive evaluation and design type, it was determined that these aspects of deductive design thinking were primarily used in subsequent evaluation. In the context of 3D design software, the most significant aspect of cognitive design was the evaluation process which was either deductively or inductively related to the expansion of thought (Lee et al, 2018).

This study also determined that designers using the CAD software made additional prototyping edits throughout the development process when compared to the group using conventional sketches. Designers with access to a 3D model frequently put their design process to a halt in order to assess their work and determine whether or not it was productive to continue with their design. On the other hand, designers using the conventional sketch method were found to maintain designs highly similar to their initial conception by using concepts found in product design history while sketching. Consequently, fast prototype and development behavior that leads to constant design iteration was determined to be more common for the group using CAD technology than the group using conventional sketches. Interestingly enough, the results of this study also show that engineers using 3D modeling software tend to create a single, well-rounded solution to a problem due to the fact that it relies on its virtual display onto a computer monitor. Most likely, this is due to 3D models being both time consuming and easily manipulable, whereas traditional sketching methods can be created quickly but cannot be edited with as much ease. Subsequently, traditional design tends to involve multiple unique designs that are chosen from whereas design intended for 3D printing often require only a single preliminary design.

3D printing has become so ingrained into prototyping and product development that this design technology has a direct impact on the designs and solutions incorporated into 3D models that engineering students create. An experiment was conducted involving a selection of design students who either crafted a prototype by hand or with 3D printing capabilities. The group with access to 3D printing incorporated a large number of curved and rectilinear shapes compared to those who lacked it, as well as other differences in design quality. Further discrepancies between these groups found in this study include differences in overall craftmanship and scale. This shows that access to 3D modeling and printing does in fact have an impact on models that students design, and it also suggests that “Students do connect ideation to implementation, and the availability of enabling technology impacts the design process” (Greenhalgh, 2016). Although these results are targeted at students, the analysis on shapes that come through access of design tools and the impact that they have on cognition, especially at an early age, translates to entry-level engineers who often have little design and manufacturing experience.

The Effect of Rapid Additive Manufacturing on Design

Other benefits further stimulate design within engineering, such as personalized design becoming readily available via 3D printing production, allowing designers to create custom and complex geometries to rapidly test things like comfort, ergonomics, and manufacturability. Due to its ability to fabricate lightweight products with very low production costs compared to traditional manufacturing, especially when considering the accuracy and detail of the prints, 3D printing is highly coveted in terms of testing unprecedented designs and geometries. This stimulates creativity in designers because they are allowed to think more out-of-the-box due to the unrestricted nature of the printing. For example, prior to 3D printing technologies engineers could only manufacture machined products by working on one face of the product and in large step sizes, causing parts to be far less detailed and more difficult to manufacture. The high resolution and layered printing capabilities exemplified by 3D printers allow virtually any design to be fabricated, enabling physical designs to be created that were impractical before.

Another aspect of design that changes due to this technology is that engineers' production efficiency can be far more enhanced than in the past. In terms of sustainability, 3D printing reduces the overproduction of plastic products, requires less storage space, and generates less waste than traditional manufacturing techniques (Fuldauer, 2019). This is primarily due to the fact that 3D printing incorporates virtually all of the material used into the design itself, whereas traditional manufacturing processes generally integrate cutting out unnecessary material, generating more waste. In other words, the only material required for production is used in 3D printing. Moreover, 3D printing on the local level diminishes the need for transportation, and consequently reduces CO_2 emissions involved in product development and manufacturing. In terms of design, engineers do not need to focus on design details surrounding waste elimination and product transportability. Industrial waste is responsible for causing significantly adverse effects on both the earth and those living on it due to the waste involved in manufacturing. Liquid and solid material waste can threaten the well-being of the food, water, and health security ecosystems (Rinkesh, 2020). The state of the environment is becoming an alarming engineering challenge and serves as a threat to society, and additive manufacturing is one technology that can be used to make design and manufacturing more sustainable. The pollution caused by conventional subtractive manufacturing methods can be reduced via source control, recycling, and cutting the frequency of transportation, all of which are highly difficult to manage. 3D printing, however, addresses all three of these issues, eliminating the vast majority of waste and transportation associated with product development and production. In terms of societal influence, widespread 3D printers enable goods to be designed on computers to be manufactured in the homes of consumers, greatly reducing the costs and environmental impacts of transportation (Cappel, 2019).

3D printers have a significant impact on a product’s lifecycle, allowing a complete prototype to be created within hours; it isn’t necessary to have engineers discuss intentions with manufacturers. Engineers can simply send the manufacturer a prototype rather than manufacturing products based solely from a CAD model, increasing sustainability. No longer must design engineers invest millions of dollars and countless hours building molds, machining parts, and creating expensive assembly processes in the hopes that their original design is adequate. With 3D printing, engineers can rapidly prototype ideas, eliminating concepts that do not work well while improving promising ideas. Alternatively, this 3D print and iterate concept could create an engineering environment lacking attention to detailed tolerance, stress points, and force vectors that are not illuminated in a 3D model. This could be devastating in real-world production. For example, printing a 3D small-scale model of a bridge or building might be great visual confirmation of stability, without yielding critical information regarding wind-shear, earthquake resilience, or thermodynamic forces.

Risk, Expertise, and Ambiguity Within Additive Manufacturing

Innovation and design are suppressed without immediate 3D printing capabilities because a designer is hampered from creating different iterations of a design in a short timeframe. In-house print abilities support engineers in constructing original designs and technologies by easily generating prototypes. If 3D printing is unavailable, artificers will design more conservatively because there is greater risk while waiting on a third-party manufacturer to create a prototype that may or may not work. Without these turnover times, a more relaxed environment exists where more time can be spent finalizing the product. This stimulates creativity, allowing product architects the ability to rapidly implement changes and test multiple physical models. Engineers are also provided additional time to consider secondary design factors such as safety, durability, and diversification products for alternate uses. Because 3D printers are constantly constructing novel technologies, it is imperative to consider the scope of unintended purposes that they can be used for. Due to the time savings provided by 3D printing, engineers are able to more rigorously test and experiment on new technologies in order to better understand their non-intended functionalities. This could also shed light on potential fail safes that can be programming into the invention in order to discourage the product being involved in unforeseen sinister purposes while still being able to meet development deadlines. Typically, when an engineer goes through the initial iterations of a product, there is one main feature intended at the design’s core. With each iteration, the design goal is stretched to include cost, time and quality (Sobek, 2003). 3D printers permit product design to reach the satisfactory point in a shorter time period, improving the overall manufacturing process with greater efficiency. Engineers then have more time to invest on seemingly less important details in the eyes of the consumer.

Although CAD tools have had positive influences on product development, questions have been raised about whether three-dimensional modeling technologies are actually beneficial to the design process (Tang et al, 2011). Even though this software enables engineers to rapidly fabricate a model of an idea, their expression is limited by the technology, particularly within the early concept design phase (Lee et al, 2018). 3D printing and modeling capabilities create an ease of design iteration and allow engineers to work with their models interactively. However, studies have shown that CAD modeling capabilities can have "a negative influence on creative design" (Bonnardel and Zenasni 2010) due to the fact that certain engineers concentrate more on utilizing computational systems rather than on their creativity or design ability when creating 3D models. This concentration is caused by certain engineers having to abide by a set of highly developed guidelines and restrictions within the confines of virtual modeling, ultimately impacting their creativity and freedom to design.

3D printing is not a one-size-fits-all solution, highlighted by Kostakis and Papachristou (2013); they reference Winners' (Winner, 2009) idea that widespread adoption of certain technologies cannot automatically produce a better world. Some technologies require appropriate social environments to be structured in a certain way for them to meet their potential (Kostakis, 2013). They suggest this may be the reason attempts for more autonomous forms of production based on novel technologies has been so common in recent decades. They emphasize that design manufacturing optimization focuses on three essential aspects: design modularization, customer intuition, and cost-efficiency. Focusing on these aspects, engineers better understand the needs and performance of products, and more practical, inexpensive changes can be implemented into designs with each iteration. Although 3D printing can drastically reduce the costs of prototyping and R&D (Owen, 2020), it does not necessarily make products more inexpensive for consumers by the time they come to market. However, because of this cut in spending, resources can be allocated to focus on other factors such as design modularization and customer intuition while maintaining increased profit margins. These factors of design also become more manageable with the technology because prototypes can be so rapidly developed, tested, and iterated within a shorter timeframe.

Grigoriadis acknowledges the possibility that rapid advancements in additive manufacturing can lead to a decrease in distributive innovation, proving it difficult for small companies to compete in quickly saturating and high performing markets (Grigoriadis, 2017). Furthermore, it causes quicker product obsolescence. When frequent prototype changes are implemented, new products and technologies follow. For example, a two-year-old version of Apple's iPhone is often considered archaic. This produces vast waste because the population is regularly upgrading its technology while disposing of the old. Firms such as Apple, Samsung and Ford use 3D designs to rapidly create prototypes that validate form, fit, and function of products and gather market feedback without the time and expense of building 'at risk' manufacturing production. Unfortunately, an unintended consequence of this swift innovation and 3D prototyping is that products can be brought to market with less manpower, equipment and manufacturing infrastructure. Instead of traditional design and manufacturing, product ideas and innovation have become decentralized and widely distributed; virtually anyone with computer CAD software and 3D printers can create new, disruptive technologies and products. I investigate how the current design industry values a short cycle-time and low development costs while emphasizing fast product-to-market speeds. However, this environment encourages engineers to think more innovatively. The expectations 3D printing has brought upon designers puts pressure on them to reveal new designs far more frequently than in the past. The most obvious examples are cell phones and smart watches, which now essentially have a 12-month lifecycle. Companies mass producing technologies such as cars, cellphones and computers release multiple products annually, gaining a competitive edge. Additionally, 3D printing tends to lower the costs of development because of its ability to avoid fees from contracting out prototypes within R&D. This creates product design entry barriers, sparking greater competition. Unfortunately, this can also result in companies easily and inexpensively replicating products, undercutting the innovator's design and market leadership. For example, Ping golf clubs, Bluetooth earbuds, and even computer processors have all been victimized by copycats using CAD tools and 3D printing to enter the market in a disruptive way.

The increased emphasis on 3D printing and its capabilities over the past few decades suggest that future technological advancements will continue to impact the way that artificers think and design. This additive manufacturing method opens the door to unprecedented product fabrication in both speed and ability to design when compared to subtractive manufacturing which can only manipulate a material in one direction. Through this technology engineering solutions are revolutionized in terms of design and speed to market, albeit concerns are raised on whether or not this result is inherently good.

Discussion

In conclusion, the impact that in-house design and manufacturing capabilities have on engineers' design process, specifically in terms of 3D printing, cannot be understated. A variety of benefits that these technologies provide allow engineers to adopt a more creative designing style due to the fact that manufacturing price and material waste are greatly diminished through this method of fabrication. Designers are more inclined to experiment with numerous designs because they can be so rapidly manufactured and tested for functionality at a very low cost, and also new designs become available that cannot be performed with traditional subtractive manufacturing. Similarly, engineers can freely create more complex designs without paying any additional cost, giving engineers that use 3D printers more freedom than those using other manufacturing methods. Rather than designing with an emphasis on ease of manufacturability, artificers can focus more on overall product design and functionality. This rapid evolution in designing begs the question, what will designing look like in the future when these technologies are even further advanced? Will sections within design become fully autonomous, requiring neither an operator nor a designer? Do these technological advancements remove certain human factors within design even though creativity can be stimulated?

Although there are many benefits, this technology has not been a one-size-fits-all solution in terms of production, and some negative aspects present themselves such as innovation and design suppression and a decrease in distributive innovation. This can produce undesirable results such as an increase in product design entry barriers, causing large corporations to perform at far higher levels among their competitors, leading to faster product obsolescence. As a result, engineering firms must weigh the pros and cons surrounding 3D printing technologies with respect to their manufacturing needs. For example, a firm that values creativity and experimentation within design are more inclined to adopt 3D printing than one that values distributive innovation above all else. For reasons including cost, usability, timing, and expression, 3D printing not only changes the engineering design process as a whole, but also has a direct impact on the way that designers think and create.

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