Chapter 13
Additive Manufacturing for Mass Customization

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Abstract Additive manufacturing (AM) is a disruptive manufacturing technology that requires no tooling for production. AM requires three dimensional computer aided design (3DCAD) data in order to *additively* build parts from numerous materials, including polymers, metals and ceramics. Within this chapter the advantages realized by taking an AM approach are considered as well as their application in mass customization MC). Particular emphasis is given to the use of AM in the production of customer generated data from a number of sources including massively multiplayer online role-play games (MMORPG).

Abbreviations

3DCAD	Three-dimensional computer aided design
3DP	Three-dimensional printing
AM	Additive manufacturing
CAD	Computer aided design
CEO	Chief executive officer
CNC	Computer numerical controlled
DFM	Design for manufacture
FDM	Fused deposition modeling
HVAC	Heating and environmental ventilation control
IP	Internet protocol
ITE	In-the-ear
LS	Laser sintering
MC	Mass customization
MMORPG	Massively multiplayer online role-play games
MPH	Mobile parts hospital
PC	Personal computer
SL	Stereolithography
STL	Standard template library
USB	Universal serial bus
WoW	World-of-Warcraft

13.1 Introduction and Background

Customization and, particularly, MC (Pine *et al.* 2000), has received a great deal of attention in recent years as a method of creating increased value for manufacturers and retailers alike. Many instances of mass customization (MC) use innovative supply chain concepts to produce customized products from a range of existing "modules" (Salvador *et al.* 2002). These modules are often manufactured using traditional manufacturing processes and therefore require investment in tooling. The cost of tooling, *i.e.,* for injection molding, pre-determines the necessary component volumes in order to manufacture parts cost-effectively. Consequently, this may prohibit new product development and therefore stifle innovation in product development, particularly for bespoke or tailored products. In addition, the ability to produce components that fit customer needs intrinsically means that the customer is intimately involved in the product design process. This chapter provides an example of the marriage between personalization and a method of production that does not require tooling investment. The chapter will present a short background on the manufacturing technology, known as AM followed by its uses and advantages. Finally, a novel concept in MC utilizing AM systems will be shown as an example for the technology, namely the production of bespoke online gaming characters.

Additive Manufacturing

AM, often known as rapid manufacturing, direct digital manufacturing and e-manufacturing amongst many others, encompasses a number of process technologies. Examples of AM include: stereolithography (SL), laser sintering (LS), fused deposition modeling (FDM), and three-dimensional printing (3DP). Although each of these processes is different, they encompass the same process philosophy. AM produces components in an additive fashion, where components are fabricated by adding successive layers of material together, driven by 3DCAD data. This contradicts traditional manufacturing techniques, such as subtractive (machining) and formative (molding) methods. AM has been defined as the production of parts or final products directly from digital data, eliminating all tools (Dekker *et al.* 2003, Tuck and Hague 2006).

From a manufacturing and marketing perspective, there are several advantages in adopting an AM approach. Firstly, design freedom (Hague *et al.* 2003); designers are free to design complex geometries that only AM machines are able to fabricate. The direct fabrication of these parts from CAD data also means that the tooling step is eliminated, hence, designers do not have to be concerned about many design for manufacture (DFM) criteria; for example, whether a geometry can be removed from a tool cavity. Additionally, due to these design freedoms, assembly operations required to make up a component that lead to an increased cost to the consumer, especially for low volume and custom components, can be reduced. Removing tooling means that changes to the design can be made quickly without significant effect on cost. At the same time, the long lead time for the delivery of tooling can be avoided, shortening the time-to-market of a product (Hopkinson and Dickens 2003). The removal of tooling has further advantages; without tooling, it is possible to fabricate parts and products in small quantities, which would not otherwise be economically viable. AM enables low volume production at a more economical cost, as shown by Ruffo *et al.* (2006). Without the cost of tooling, the cost of low volume production by AM can be significantly lower when compared to traditional manufacturing processes. Numerous studies have been carried out to discern the differences in costs between AM and traditional manufacturing techniques, selected references include work by Hopkinson and Dickens (2001) and Ruffo *et al.* (2006).

AM is a disruptive technology that holds promise in the development of MC in particular for complex and/or body fitted components where geometry is particularly important. However, as with many technologies it is necessary to understand the underlying benefits and investments required for such technology to exist in today's manufacturing enterprises. The benefits discussed above are linked to the potential geometric complexity afforded by the technology and the removal of tooling from manufacture. The technical investments necessary to carry out AM are not too different from many other modern production technologies, for example CNC machining. The precursor to any AM produced component is a 3DCAD model of the item, normally in the format of an. STL file, a common option on commercial CAD packages. The file is then positioned and placed in the "build envelope" by a skilled technician. This build packet is then uploaded to the primed AM machine where the parts are built autonomously. After the machine has completed the build process the parts are removed and post-processed to remove any extraneous materials or supports. The level of investment required to enable an AM manufacturing facility is a function of the manufacturing technology being used; this can vary from a few thousand dollars to many US $100's of thousands with associated differences in the necessary infrastructure required. Labor requirements *during the process* are low. However, skilled labor is required to setup the build files and orient the parts in the virtual build envelope and set up the machine for manufacture. Following manufacture, the parts need to be "cleaned up" ready for the customer, which may include coating or other surface treatments.

AM has already been adopted in several industries, including in-the-ear (ITE) hearing aids (Dickens *et al.* 2005; Wohlers 2003), automotive (Tromans 2006, Kochan 2003) and aeronautical industries (Amato 2003), for the production of some parts. Major hearing aid companies have adopted AM as their mainstream production technique for ITE hearing aids. Siemens Hearing Instruments has been producing customized ITE hearing aids using AM techniques at a production rate of 2000 pieces *per* week (Masters *et al.* 2006). Traditionally, the manufacture of ITE devices required a great deal of skilled labor in the production of the customized hearing aid shell, and was thus dependent on the abilities of the technician undertaking the work. The introduction of CAD technology and particularly the use of three-dimensional scanning methods have enabled much of this design process to be digitized. An audiologist, using wax-like materials, takes a physical impression of the outer ear; digital information is captured using a non-contact 3D scanner, either at the audiologist or at the manufacturer. It is important at this stage to get good and accurate data as this will determine the fit of the ITE device, which directly impacts on the ITEs in-service performance. The scanned data is then processed into a suitable CAD file and the necessary operations for accommodating the electronics carried out. The final shell is then sent to an AM machine (commonly, SLA or the Envisiontec Perfactory process) and the final shell fitted with the electronics and sent to the consumer. This method has greatly reduced the uncertainties in producing a custom-fitting item, yielding a greater degree of consistency in the product.

In the aeronautical industry, heating and environmental ventilation control (HVAC) systems inside fighter jets are printed out by AM machines, and have led to savings and reductions in cost and production schedules of about 50%. In other defense applications, the US military has set up a mobile parts hospital (MPH) at sites in Kuwait and Iraq, printing replacement parts for damaged equipment. The army is able to replace broken parts within hours instead of waiting days or weeks for the new replacement (Aston 2005). Besides industrial usage, AM has also been adopted in consumer products. MGX, a division of Materialise of Belgium, has been using AM technology for the fabrication of customized and limited edition lamps with complex designs (MGX, 2007).

The availability of customization has been possible with advances in manufacturing technology, enabling low volume production to be achieved efficiently. AM is envisaged to be the enabler for many types of customization (Tuck and Hague 2006, Dickens *et al.* 2005). As discussed earlier, the development of tool-less production enabled by AM makes it economically viable for small volume production. As such AM would be suited to cater for niche markets requiring unique end products. This fits well with the requirements of customization, which manufactures a product or delivers a service in response to a particular customer's needs (Pine *et al.* 2000). This in turn means producing a one-off item. With a greater degree of design freedom, AM is potentially able to cater to almost any geometric requirements.

As we have already seen, AM has found a number of MC uses, ranging from small volume applications such as the MPH to high volume applications such as ITE hearing aids. However, in all these cases, the geometric data used to drive the AM process has been captured using secondary scanning technologies and expert systems software. For the true MC potential of AM to be fully exploited, the technology must be coupled with consumer driven or "enabling" software, that is capable of producing high quality data.

At present most 3DCAD systems are beyond the capabilities of the untrained user. However, both online design tools and design tools embedded into computer games have already been developed to be used with no formal tuition beyond the on-line help page. It is this freedom of user generated content that has enabled a small but growing number of companies to exploit the MC freedoms of AM by coupling the technology with both simple internet based design applications and interactive computer games packages.

13.2 AM and the Realization of Mass Customized Internet Content

Although the consumer has been able to purchase AM products online for a number of years from companies such as Freedom of Creation and Materialize MGX, it is only since mid 2006 that the consumer has been able to engage in the actual design process, using web based tools, prior to the delivery of their tangible AM product.

Probably the earliest example of using AM to enable the manufacture of online "consumer described" content was the launch of www.fabjectory.com by Mike Buckbee in 2006 (Fabjectory Website 2009). The Fabjectory business model enables players from the Metaverse "Second Life" to purchase models of their individually designed avatar characters manufactured using Z-Corporation 3D-printing. Unlike other MMORPGs, the creators of Second Life, Linden Laboratories of San Francisco USA, have assigned all intellectual property rights for characters, building and vehicles to the game's user (Wagner 2008). This, in essence, gives the estimated one million Second Life "active residents" the right to exploit their own designs. This has led to a number of interesting business cases, where real-world clothing brands have been developed based on virtual world designs. Moreover, this also allows every Second Life user to extract the geometric and render data of their individual avatar characters and provide this to Fabjectory for 3D printing, without any infringement of Linden Laboratories intellectual property. On the other hand, this also represents the weakness in the Fabjectory business model. As Fabjectory retains no control of the 3D data enabling the AM supply chain, any "secondlifer" can extract their own data and send this to be printed by their local 3DP service provider.

To close this loop hole in lost revenue, the first truly integrated online AM fulfillment business was launched in Singapore in early 2007 by Genometri PTE Ltd., a spin-off company from the National University of Singapore. Trading under the brand name Jujups (www.jujups.com) the company has developed an interactive 3D design "portal" that allows web users to design a range of simple "giftware" products such as photo frames, key fobs, tokens, USB flash drive casings and personalised Christmas decorations. The resulting designs are then additively manufactured using a Z-Corporation full color 3D printing system before being dispatched directly to the customer.

According to Genometri CEO Sivam Krish the system uses a series of simple web based JavaScript design tools. This allows users to select from a pallet of 3D objects. Examples include picture frames that can be personalized with text, relief objects such as flowers, or with photo images uploaded directly by the user from the home PC or laptop. On completion the "virtual design" can be saved and shared with others or committed to print, at which point payment is made by credit card. As a closed loop system, all resulting 3D data remains within the Genometri Ltd. fulfillment model and as such cannot be extracted and printed by an external third party. Interestingly, Genometri does not own its own AM hardware, but relies on a network of 3D printing service bureaus located in Asia, the USA, and Europe. This concept of distributed additive manufacturing will be discussed later.

A similar closed loop AM fulfillment model to Jujups has been developed by the 3D Outlook Corporation in the USA, where users are able to select topographic data of the earth's surface online, and use this as the basis for a three-dimensional color relief map printed in a selection of sizes. Figure 13.1 shows how the technology has been used to create a three-dimensional relief map of the Grand Canyon.

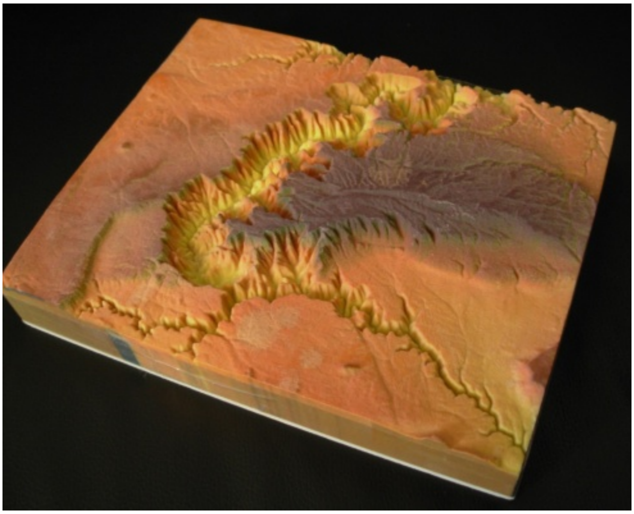

Figure 13.1 3D printed topographic representation of the Grand Canyon (copyright Econolyst Ltd.)

The system uses a JavaScript web interface (www.landprints.com), (Landprints Website 2009), which is linked to the US geographic survey mapping database of the contiguous United States. Users first select the area they are interested in printing, using a "Google-earth" style application, which can be rotated and zoomed. Once selected, the two- dimensional topography including roads, rivers, and lakes can be given an exaggerated or to-scale three-dimensional depth, using an online *Z*-axis height slider. Once the height of the model is selected, the user decides on the model size with options of 5", 6", and 8". A credit card payment is then taken of between US $37.95 and US $69.95, with delivery guaranteed within 2 weeks. The offer is currently aimed at town planners, councils, architects, and development site owners. However, there are also plans to allow users to upload their own topological data or imagery in the future.

Although websites such as Jujups, Landprints, and Fabjectory have identified and exploited possible mass customization applications for AM, they appear to be constrained in their marketing channels to the internet, possibly with the exception of Landprints who could advertise in trade journals. An alternative methodology of engaging the consumer with MC AM is to integrate the technology with an existing software package such as a PC based computer game or web based MMORPG.

13.3 The Integration of Additive Manufacturing with Computer Games

The first fully integrated AM business model within the computer games industry was launched in December 2007 by US business start-up FigurePrints (www.figureprints.com), (Figureprints Website 2009). FigurePrints is an exclusive licensing partnership between a former Microsoft executive, Ed Fries, and global software house Blizzard entertainment. The FigurePrints website allows players of the MMORPG World-of-Warcraft (WoW) to order 1/16th scale models of their online gaming character, manufactured using full color AM. However, unlike Second Life where the character IP resides with the designer, all WoW character definitions remain the exclusive intellectual property of Blizzard entertainment, albeit they are designed using a suite of "character building tools" by the games players. Hence, FigurePrints provides a previously unimaginable licensing opportunity for Blizzard and a means for emotive gamers to realise on screen characters in real life. By March 2008 FigurePrints had received over 100,000 enquiries for characters costing US $140 each (Wohlers 2008). By December 2008 these orders were being fulfilled using six in-house Z-Corporation Z510 color 3D printing machines. However, demand still appears to far outweigh supply, with order fulfillment being based on a monthly lottery system governed by the companies' capacity to produce a maximum of 1,700 characters *per* month (as at December 2008).

Although it is possible for anyone with knowledge to extract WoW characters from the model viewing software, as shown in Figure 13.2, and to re-render this using commonly available software such as 3D Studio Max, this would be considered a breach of Blizzard Entertainment's copyright if the parts were ever sold, and as such will prevent any commercial competition to FigurePrints within the near future.

Figure 13.2 World of Warcraft model printed using Z-Corp 3DP (copyright Econolyst Ltd.)

It should be noted that WoW currently has 11 million registered players. Hence FigurePrints current penetration represents less than 1% of the potential market by enquiries, and a fraction of 1% in terms of paying customers. Nevertheless, based on the current limited production capacity the business still has the capability to turnover in-excess of US $2.85 million *per annum*.

Following the rapid and somewhat unexpected success of FigurePrints, AM technology vendor Z-Corporation of Massachusetts USA (www.z-corp.com) have now established their own 3D printing service "Z-Prints" to service the online and platform computer gaming sectors. To date the company has 3D printing agreements to support the computer games "Rock Band" (www.rockband.com/merch), (Rockband Website 2009) and "Spore" (www.sporesculptor.com), (Spore Website 2009), both published by global games leader Electronic Arts (EA). A typical 3D printed Spore character, which would cost US $49.95, is shown in Figure 13.3; this compares to a WoW FigurePrint costing US $140.

Interestingly, in addition to purchase price there is also a question of "emotional value" when considering the cost of 3D AM games characters or avatars. Spore and Rock Band characters, although fully defined by the games players, could have a limited emotional attachment for the gamer, as they are easy to design and modify and therefore easily re-created. This poses the question:

> *Do I really feel emotionally attached enough to my games character to part with hard cash just to see it printed out?*

Figure 13.3 EA Games, Spore character printed using rapid manufacturing (copyright Econolyst Ltd.)

This differs greatly from FigurePrints where WoW gamers often play the same character for many hundreds if not thousands of hours, building up an emotional bond that may drive the gamer more towards the purchase of a tangible avatar. Research by Wolfendale (2007) suggests that MMORPG players can develop a form of "avatar attachment", where the avatar becomes an extension of the gamers' persona. To have a tangible 3D representation of this persona is therefore a natural expression of personal vanity, very much like a photograph of your latest skiing holiday or a family portrait. It is this level of avatar attachment that may in the future be the driver behind successful computer games enabled AM business.

Within both Rock Band and Spore, gamers have the option to design their own characters, prior to committing to a 3D print. At no stage, however, does the gamer gain access to the 3D geometric or render data, as this is passed only between the software and Z-Corp, ensuring that models cannot be printed externally, which would lose revenue for both Z-Corp and EA. Unlike FigurePrints, the Z-Corp business model works on a traditional order and fulfillment principle, with parts being manufactured following order for immediate dispatch. The costs of 3D characters produced by Z-Corp are also noticeably lower than other online offerings such as FigurePrints, although they are slightly larger. This appears to be a function of the models being manufactured on lower resolution, lower cost machines, but it can also be assumed that Z-Corp are using their own 3D printing machines and materials supplied nearer to cost price.

13.4 Poachers and Gamekeepers

The result of an AM technology vendor becoming a service provider poses a significant challenge for other businesses wishing to operate in this domain, as it is difficult to see how anyone can compete in price against a business that also controls the machine, maintenance, and material supply channels of its competitors. However, the Z-Corporation business model may have some weaknesses if it is to support truly globalised AM product customization.

At present Z-Corp has opted for a "centralized factory" configuration, with all 3D printing capacity located under one roof in Massachusetts. Although a cost effective methodology for supporting the North American market, it may be limited when trying to supply the entire potential consumers base, as almost all computer games are now sold on a global basis. One of the most significant limitations is postage and packaging costs. Z-Corp models are relatively fragile and require careful packaging prior to shipping. Hence, many fine feature games character models are initially placed under a glass or Perspex dome and glued to a rigid base. This can result in relatively high shipping costs as a percentage of the product value. Moreover, using this centralized production model, lead-times between product order and fulfillment are increased relative to the length of the transportation phase between the customer and the Massachusetts based production facility.

Of course, the alternative is to locate manufacture nearer to the consumer. However, traditional supply chains have resisted this notion as it requires expensive duplication of fixed assets such as injection mold tooling, jigs, fixtures, and specialist production equipment. For example, a typical injection molding tool for a small games character could cost in the order of US $5,000. Hence, if production were required in four different locations, US $20,000 of tooling would be needed. Moreover, this tooling would only be able to make a single product design. Hence, the production model would be one based on mass production to amortize the tool investment. With AM, however, there is no need for such capital investment in tooling, as the technology operates independently and discreetly. Still, there is an initial investment in the 3D printing technology, which can cost between US $45K for a color Z-Corporation printer, up to US $500K for a high throughput polymeric laser sintering system. But this is no different to the investment needed in, for example, the injection molding machine. However, the AM technology is then capable of producing an infinite variety of different products without additional capital investment. Hence, AM can be used to make the same part or multiple versions of a part at multiple locations with no additional cost.

This concept of "distributed additive manufacture" is currently being developed by one of the authors for the production of computer games characters and other additive manufactured products under the brand www.per-snickety.com (Per-snickety 2009). Per-snickety uses a networked approach to distributed manufacture. The Per-Snickety concept is based around a centralized "print-queue", which is feed by multiple data sources, such as computer games, online design orientated websites or simply by companies looking to source AM models. The print queue is then accessible only to validated Per-snickety print partners, who can then download complete platforms of work to place on their machines for a pre-agreed price. The Per-snickety concept is to use underutilised machine capacity on Z-Corp 3DP machines and polymeric laser sintering machines. Upon completion the AM parts are shipped directly to the consumer by the Per-snickety print partner.

It is hoped that as global demand for Per-Snickety increases, so part files in the print queue will be automatically routed to the closest available machine to the consumer, reducing shipping costs and the carbon footprint of the entire supply chain.

13.5 The Future

Although they are still in their infancy, centralized and globally distributed AM supply chains could be a short lived phenomenon as home based additive technologies become a commercial reality. Pasadena based Desktop Factory (www.desktopfactory.com) are close to launching a sub-US $5,000 polymeric based additive technology that will be in offices in 2010 and could be in homes as early as 2012. The system, which is shown in Figure 13.4, does have its limitations, as it can only produce relative small (4" × 4" × 4") models in a single color.

Figure 13.4 Beta test version of desk top factory low cost AM machine (copyright Econolyst Ltd.)

However, it is not inconceivable to imagine the technology both reducing in price and increasing in functionality with the addition of color and an increased build envelop. AM of MC internet design and computer games characters could then become as common as the home printing of photographs, or the playing of downloaded music or video media. In the future we could be in a position to download and 3D print new product designs, or as shown, engage in part of the design process prior to purchasing our design for home based digital fabrication.

But we must not lose sight of the data originators in this future supply chain and their brand identity, as this is key to any company engaged in both virtual or tangible product design and realization. Where the end user can manipulate a design, brand control becomes paramount, as without sufficient safety measures the end-user could in effect destroy the brand through the creation of poor quality design. Within AM, this could be manifested in the user designing a product, such as a computer games character or avatar, which is too detailed for the AM process, resulting in a part with missing features and a poor perceived quality, hence impinging the quality of the brand. One solution would be the “free issue” of data to users with the caveat “print at your own risk”. However, this would require the release of core intellectual property data including both the geometric and color information relating to the design. Even based on a “pay-to-download” business model, this would in effect allow the user access to make multiple copies of their design with no ongoing revenue to the data provider. Other considerations include health and safety, product liability, and recyclability.

13.6 Implications of AM for MC Businesses and Future Research

The implications of AM on the potential of MC businesses that deal in physical products, particularly those that have significant consumer geometry or generated content are profound. The overarching benefits of taking an AM approach to manufacture lie in the removal of tooling from the manufacture of the physical product. The connotations of removing this tooling are potentially profound as it removes restrictions throughout the product development and production process. Previous work has shown the potential for AM to significantly change paradigms for design, production, and supply chains.

The amalgamation of customized content, whether it is user-generated or user-specific, with AM has enabled the successful manufacture of numerous products in very disparate markets, *i.e.*, from the computer gaming market to the medical arena. This potential to affect different markets with a single manufacturing technology genre is rare and requires further investigation by both the academic and business communities. Aspects such as the enabling of consumer co-design and use of customer data (Campbell *et al.* 2003), the implications on custom fitting products (Custom Fit 2009) are all being targeted by practitioners of the technology. In addition, work has begun on other aspects of AM particularly in the implications to business and supply chains. Recent work by Tuck *et al.* (2007) has discussed the potential implications for AM on supply chain methodologies and practices. Discussing the potential effects of AM on traditional supply chain methodologies, a number of benefits could be attributed to existing supply chain management practices such as lean, agile, and Postponement. In brief, the ability to make what you want when you want and where you want it has profound impact on the types of methodologies that can be developed for MC applications. AM is an inherently agile process requiring little in the terms of setup to produce different parts. In addition, these different geometries can be potentially built at the same time, on the same machine platform. This has an obvious impact on the practice of modularization (Salvador *et al.* 2002). Though not superseding the practice of modularization, AM may be able to facilitate the modularization activity in a different way. The ability to hold stock as digital data and print on demand has potential for manufacturing the modular components commonly used for MC on demand. This could potentially push postponement points further downstream enabling the supply chain to become leaner upstream and pushing the customization downstream, potentially to the retailer or even the consumer.

13.7 Summing Up

In conclusion, AM holds a great deal of promise for the MC community. The additive manufacture of mass customized computer games and internet content has been an exciting example, coming from nowhere to a multi-million dollar industry almost within months, let alone years. Much of this is due to the low barriers to entry, but also the ability to provide the consumer with something they have never had before, a tangible way to turn computer designs into mass customized 3D products. However, these supply chains are not simple, as they rely on finding a common ground where the consumer, the games developer, and the 3D printer are all winners.

Acknowledgments The contributions of Ed Fries (FigurePrints), Sivam Krish (Genometri PTE), and Dr Ian Gibson (National University of Singapore) are all gratefully acknowledged.

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